EVALUATING THE PERFORMANCE OF PLAIN AND BLENDED CEMENT CONCRETES UNDER MARINE ENVIRONMENT IN THE ARABIAN GULF

BY

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*Dedicated to my beloved **parents** and **family members***

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THESIS ABSTRACT

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A reduction in the useful service-life of reinforced concrete structures, due to premature deterioration of concrete, is a major problem in the countries along the Arabian Gulf. The cause of deterioration is a combination of the aggressive environmental conditions, marginal quality of the aggregates and improper workmanship. In the coastal areas, the problem is further accentuated due to the high salinity of the seawater and high humidity of the atmosphere. The proper selection of materials and mix design parameters are among the most important preventive methodologies. For this purpose, it is necessary to develop a database on the performance of materials and design parameters under the local environmental conditions. Since most of the structures are located on the coastal areas in the countries along the Arabian Gulf, there is an interest in studying the performance of structures in sabkha and marine environments.

In this study, the performance of Type I, Type V, silica fume, fly ash, blast furnace slag cement and superpozz concrete specimens exposed to a marine environment was evaluated. The concrete specimens that were placed in an exposure site along the Arabian Gulf for the past 10 years were retrieved and they were tested to evaluate the effect of local marine conditions on their mechanical properties and durability characteristics. The durability characteristics were evaluated by measuring water absorption, water and chloride permeability, chloride and sulphate concentration, alkalinity, carbonation, reinforcement corrosion and electrical resistivity. The effect of the marine environment on the mineralogical changes of the concrete specimens was evaluated by Scanning Electron Microscopy (SEM) coupled with Energy dispersive x-ray spectroscopy (EDS).

The performance of blended cement concretes was noted to be better than that of plain cement concrete in terms of durability in the three zones, namely tidal, below ground and above ground. The results of the present study are in agreement with those reported for other exposure sites around the world.

ملخص البحث:

الاســــــــم: أحمد بن محمد نور الدين حسن.

عنوان البحث: تقييم أداء الخرسانة المخلوطة في البيئة البحرية بمياه الخليج العربي.

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إن من أهم أسباب قصر العمر الافتراضي للمنشآت الخرسانية الواقعة على الخليج العربي تعزى الى مجموعة من الظروف البيئية الحرجة وهي المشكلة الرئيسة التي تواجه الدول الواقعة على الخليج العربي. واسباب هذا التدهور يعود إلى عدم ملائمة الجودة الهامشية للحصباء والمصنعية الغير سليمة. وهذه المشاكل تزداد في المناطق الساحلية بسبب ارتفاع الملوحة في مياه البحر وارتفاع نسبة الرطوبة الجوية وكذلك ارتفاع مستوى المياه الجوفية. إن الاختبار السليم للمواد يعتبر من بين المنهجيات الوقائية الاكثر اهمية، ولتحقيق هذه الغاية فإنه من الضروري ايجاد قاعدة بيانات لأداء المواد المعرضة للظروف البيئية المحلية في منطقة الخليج العربي. وهنالك اهتمام كبير لإجراء دراسة لتقييم أداء هذه المنشآت في بيئة منطقة السبخة والبيئة البحرية.

ومن خلال هذه الدراسة، تم تقييم أداء الخرسانة التي تستخدم النوع (I)، والنوع (V) من الاسمنت المخلوط بمادة السيليكا المتطاير(Silica Fume) والرماد المتطاير(Fly Ash) وخبث الحديد(Blast Furnace Slag). وتم تعريض هذه الانواع من الخرسانة في محطة الأبحاث الواقعة على الخليج العربي والتابعة للهيئة الملكية في مشروع الجبيل على مدى العشرة سنوات الماضية. كما تم اختبارها لتقييم مدى تأثير الظروف البيئية المحلية على خصائص متانة الخرسانة.

وتم التقييم لخصائص متانة الخرسانة من خلال قياس امتصاص المياه وكلوريد النفاذية ومادة الكلوريد ونسبة تركيز الكبريتات والقلويات والكربنة بثاني اكسيد الكربون وتآكل حديد التسليح والمقاومة الكهربائية. وكذلك تم تقييم مدى تأثير البيئة البحرية على التغييرات التي تطرأ في عينات الخرسانة من خلال استخدام المجهر الالكتروني (scanning Electron Microscopy) إلى جانب قياس اطياف الاشعة السينية المبددة(Energy Dispersive x-ray spectroscopy).

وقد لوحظ ان اداء خرسانات الاسمنت المخلوطة بالمواد البوزولانية أفضل من خرسانة الاسمنت العادية من حيث المتانة في مناطق التعريض الثلاثة وهي: منطقة المد والجزر(Tidal) ومنطقة تحت الأرض(Below Ground) ومنطقة فوق الأرض(Above Ground) في محطة الابحاث. إن نتائج هذه الدراسة تتوافق مع تلك التي وجدت في أماكن تعرض مشابهة حول العالم.

CHAPTER 1

INTRODUCTION

Marine environment is the condition prevailing in and around the vicinity of an ocean or a sea. Coastal areas that can be characterized to have a marine climate, reach normally some 10 km from the coastline, due to wind-blown salt mist. The study of concrete in this environment deserves special attention. Reinforced concrete structures in the marine environment of the Arabian Gulf are exposed to very severe conditions due to the high salinity of the seawater and high ambient temperature. It is reported that the salinity of the Arabian Gulf seawater is about six times that of the other seawaters. The deterioration of concrete structures in this region is further accentuated due to the marginal quality of the aggregates. Under such conditions, it is imperative to select appropriate materials in order to achieve the designed service-life of structures. Although, high cement content, low water to cement ratio concrete is normally specified for marine exposure, it is also recommended to use silica fume for such conditions. However, it is necessary to develop long-term data on the performance of plain and blended cement concretes under the local conditions for a more rational use of materials under such severe exposure conditions.

In this study, the performance of Type I, Type V, silica fume, fly ash (ordinary and highly reactive) and blast furnace slag cement concrete under the local marine conditions for the concrete specimens placed for ten (10) years at Khaleej Mardumah Research Station in Jubail, Saudi Arabia was studied. The data developed in this study were utilized to assess the most suitable concrete mixture composition for the local marine condition.

1.1 Arabian Gulf Condition

The geomorphic and climatic conditions in the Arabian Gulf environment are characterized to be humid, hot-arid, relatively shallow, and highly saline groundwater and large fluctuations in temperature and humidity between day and night. The water table is less than 2 meters over a considerable part of the region and is extremely saline, with salt

content (NaCl) reaching up to 100,000 ppm (10%). Sulphates are present in quantities of up to 4,000 ppm (0.40%). The maximum daily temperature during summer reaches up to 45ºC (113ºF) with soil temperature near the surface reaching up to 47ºC (117ºF). The concrete surface temperature frequently reaches up to 70ºC (158ºF) in summer.

Sabkhas are widespread along the coastal areas of the Arabian Gulf. These areas are characterized by highly saline groundwater. Chloride and sulphate ion concentrations of a typical sabkha are 157,200 ppm (15.7%) and 5,450 ppm (0.54%), respectively. For the Arabian Gulf seawater, these values are 36,900 ppm (3.67%) and 5,120 ppm (0.51%), respectively [1].

Strong surface winds are common in this region. Gusty winds occur normally during the time of maximum temperature during the period from noon to sunset. These strong winds produce blowing sand and dust in the atmosphere that settles on the structures. The relative humidity could range from 40 to 95% over a 24-hour period.

The high groundwater salinity and high temperature make this region one of the world's most aggressive exposure sites for concrete construction. This problem is coupled with the facts that locally available aggregates are of marginal quality. Moreover, casting of good quality concrete is difficult in the hot and windy seasons that prevail in the region.

The extreme hot-arid, and humid climatic conditions in the region are particularly conducive to creating special problems in the preparation, placement, and curing of concrete as well as resulting in rebar corrosion, salt attack crystallization, and other physical disintegration processes. A rule of thumb in reaction kinetics suggests an increase in reaction rate by a factor of two for every 10ºC rise in the temperature. Hot weather conditions result in the reduced workability, strength and dimensional stability of concrete components.

The conjoint effect of chloride and sulphate salts in ground water and the high atmospheric temperature on reinforcement corrosion is described below.

The marine environment presents one of the most severe exposures to the marine environment, as it leads to reinforcement corrosion and salt scaling. The extent of deterioration depends on the exposure zone. For example, the deterioration in the splash is more than in the atmospheric and submerged zones. Submerged structures and buried structures located near the groundwater table along the shoreline are subject to sustained contact with salt contaminated water. Chlorides diffuse into concrete mainly by ionic diffusion thus leading mainly to reinforcement corrosion. Deterioration due to salt weathering is also noted. In the hot weather conditions, this problem is aggravated due to high temperature.

1.2 Concrete in Marine Environment

The marine environment is generally divided in to four zones, namely submerged, tidal, splash and atmospheric. The concrete in the submerged zone is permanently submerged in water and therefore the deterioration in this zone is very minimal, due to the lack of oxygen. Further, the concrete surfaces in the submerged zone are generally coated by a protective coating of a low permeability $Mg(OH)_2$ and $CaCO_3$ formed by ion exchange reactions with other compounds of seawater. Therefore, the penetration rate of chlorides into these structures is often considerably less than that in the other zones. Structures in tidal or splash and spray zones are subjected to cyclic exposure to seawater. The ingress of chlorides into the concrete in these zones is supported by capillary absorption of the seawater upon direct contact. Capillary absorption gains importance as the degree of drying between the individual wetting periods increases. The splash and spray zone are sometimes referred to as the atmospheric zone as per Mehta [1]. Table 1.1 summarises the primary chloride transport mechanisms applicable to structures in various exposure zones in a marine environment. The structures in the splash zone are exposed to both chloride and oxygen; consequently, the deterioration in this zone will be the maximum.

Table 1.1 Primary Chloride Transport Mechanisms in Marine Structures [1].

Exposure zone	Example of structures	Primary chloride transport mechanism
Submerged	Substructures below low tide	Diffusion
	Basement exterior walls or	Permeation, diffusion and possibly

	transport tunnel liners below low tide. Liquid containing structures	Wick's action
Tidal	Substructures and superstructures in the tidal zone	Capillary absorption and diffusion
Splash and spray	Superstructures exposed to splash water	Capillary absorption and diffusion (Also carbonation)
Coastal	Land-based structures in coastal areas or superstructures above high tide in river estuary or body of water in coastal area.	Capillary absorption (Also carbonation)

The environmental conditions in the coastal areas of the Arabian Gulf are no exception and reports have been coming with cases reporting a reduction in the useful service life of concrete structures in this region [2,3]. The environment, soil, groundwater, and seawater are heavily laden with salts that are conducive to the initiation of the deterioration processes in concrete. In marine structures, reinforcement corrosion and salt scaling are the major forms of concrete deterioration. Furthermore, marine environment, because of physical and chemical factors, is perhaps the most severe aggressive environment to the concrete structures. Major types of deterioration are noted in the tidal and splash zone. Minor deterioration of concrete mostly due to the biological growth is noted in the tidal zone. Sulfate attack is generally not noted since the presence of both chloride and sulfate ions in the seawater does not favour the formation of gypsum and hence ettringite. However, marine environment presents a severe environment not much work has been done to study the effect of this exposure condition on concrete performance. Experiences and feedback from the field indicate that improvements are still needed in marine exposure conditions for improving concrete specifications, such as making concrete that is impermeable. Majority of the work has been laboratory-based but of late, a few field studies have been reported.

1.3 Concrete Deterioration in a Marine Environment

Two forms of deterioration, namely reinforcement corrosion and salt weathering, are mainly reported in a marine environment. Biological and weed growth are noted. Reinforcement corrosion is mainly noted in the tidal and splash zones and it is mainly chloride dominated. The precise role that chloride ions play in the corrosion process, however, is not clear. Most researchers believe that the chloride ions initiate the corrosion

reaction by depassivating the natural oxide film on the steel surface, allowing the iron to dissolve into solution. The type and nature of reinforcement corrosion in the marine environment is similar to that in the atmospheric zones.

Corrosion of steel in concrete is an electrochemical process requiring the presence of moisture and air. In the presence of chlorides, when the passive film somehow gets disrupted, the electrical resistivity of the concrete plays an important role in protecting the steel from further corrosion. Gjorv [4] showed that the Ohmic resistance of concrete substantially increased by increasing the silica fume dosage. Al-Amoudi [5] studied the performance of blended cements in resisting reinforcement corrosion when the specimens were exposed to chloride-sulfate environments. He reported that the corrosion current density on the steel in fly ash, blast furnace slag and silica fume cement concrete specimens was 3, 13, and 120 times lower than that in the ordinary Portland cement concrete specimens. Byfors conducted investigation into the chloride diffusion characteristics of paste samples prepared from silica fume and fly ash cement blends. He reported that silica fume and fly ash inclusion considerably reduced the chloride diffusion rate. By conducting measurement of pH in extracted pore solution, he concluded that although mineral addition reduced the pH, the addition of silica fume or fly ash in appropriate quantities could significantly decrease the chloride diffusion and extend chloride-initiated reinforcement corrosion.

In a study conducted by Costa et al. [6] on chloride penetration into concrete in marine environment, it was reported that the durability of concrete structures exposed to marine environment depends mainly on the ability of concrete to decrease the diffusion of chloride ions. This complex phenomenon depends on many parameters related to the concrete properties and to the micro-environmental characteristics. The results show that the chloride penetration is strongly dependent on both the concrete quality and the exposure conditions.

As for the deterioration of concrete structures in the Arabian Gulf region, it is basically a corrosion problem which is particularly significant in marine environments. In part this may be due to the fact that the chloride content in the Arabian Gulf is about 1.6 to 2 times as high as the seawater elsewhere in the world.

In the severe environmental exposure conditions that prevail in the Arabian Gulf region, durability is still the most important factor for the service life of most concrete structures, both in terms of economy and safety. Of the various types of deterioration mechanisms, reinforcement corrosion is at present considered to be the main cause of premature failure of reinforced concrete structures.

Several studies have been conducted on the performance of both plain (Type I and Type V) and blended cement concretes in the marine environment. A significant number of completed research studies have shown the influence of cement types on reinforcement corrosion. The research on cement types in marine environment has generally shown that the main cement component that affects reinforcement corrosion is the tri-calcium aluminate (C_3A) which varies among the cement types. Recent studies conducted at KFUPM/Research Institute [7] have shown that the type of cement has a significant effect of reinforcement corrosion. In the concrete specimens exposed to soil and solution with varying chloride concentration, Type I cement blended with 7% silica fume performed better than Type I and Type V cements.

Ching [8] in his study on the effect of sulphates and chlorides on high strength palm oil fuel ash (POFA) concrete used POFA as blended mix in marine environment and found that the diffusion of sulfate and chloride salts into the concrete was low. A study on blast furnace slag cements for concrete durability in marine environment [8] was carried out. It indicated that the slag cement gave a very high early age resistance against chloride penetration, which may be specifically important in concrete construction work in marine environment.

The performance of blended cements in resisting reinforcement corrosion in chloride-sulfate environments was evaluated in a study conducted by Al-Amoudi et al. [5]. In that study, the concrete specimens were exposed to a simulated sabkha environment. The chloride and sulfate concentrations used were typical of the groundwater salinity in the coastal areas of the Arabian Gulf (Cl^- = 15.7% and SO_4 = 0.55%). The reinforcement corrosion was evaluated by monitoring the corrosion potentials and measuring the

corrosion current density. The corrosion potential curves were utilized to evaluate the time of initiation of reinforcement corrosion using the ASTM C 876 criterion. The corrosion current data indicated lower corrosion activity in the blended cements compared with the plain cements. The corrosion current density on steel in the fly ash, blast furnace slag, and silica fume cement concrete specimens was 3, 13 and 120 times lower than that in ordinary Portland cement. This was attributed to the dense microstructures of the blended cements. The dense microstructure in the blended cements impedes the diffusion of oxygen and moisture that are necessary for the cathodic reaction. Further, the electrical resistivity of blended cements, being considerably higher than that of the plain cement, the flow of corrosion current from anodic to cathodic sites and vice versa is discouraged.

The use of blended cements prepared with supplementary cementitious materials, such as fly ash, silica fume, and blast furnace slag, are recommended in sulfate environments [9,5]. The sulfate resistance of such blended cement concretes depends on the composition and physical properties of concrete as well as type and concentration of sulfate ions. The improvement in sulfate resistance of fly ash and silica fume based blended cement concretes is reported. The increased sulphate resistance of blended cements is attributed to the pore refining and pore refinement effect occurring due to the pozzolanic reaction where calcium hydroxide becomes bound by fly ash or silica fume converting it into secondary C-S-H gel [10,11]. However, with additional cementitious materials, the complexity of sulfate attack becomes even greater. Taylor [12] pointed out that since slag has low alumina content, it improves the sulfate resistance, but with a high content of alumina, the reverse is the case.

1.4 Need for this Research

Accelerated deterioration of concrete, particularly in the coastal and marine areas, is a very well documented phenomenon. The deterioration is attributed to the highly salinity of the seawater, elevated ambient temperature and the marginal quality of the local aggregates. Several measures have been taken to minimize the deterioration or to prolong the useful service-life of the structures. Major organizations, such as Saudi

Aramco, SABIC, Royal Commission for Jubail and Yanbu, specify the use of high quality concrete in such environments. However, the type of concrete to be used in such environments is still a point of debate since results on the long-term performance of these materials is lacking. A database on the performance of plain and blended cements under the local marine environment is also highly desirable. Such database can be utilized to develop monogram for selecting appropriate materials for the expected exposure conditions. Apart from measuring the strength and durability of the blended cement concrete in marine environment, techniques such as Scanning Electron Microscopy (SEM) were used to analyse the crystallization of cement with blended materials.

1.5 Objectives

The overall objective of this study is to evaluate the performance of plain and blended cements exposed to the local marine environment. The specific objectives are the following:

1. To assess the relative performance of plain and blended cements exposed to local marine environment,
2. To evaluate the morphological and mineralogical changes in the plain and blended cements exposed to the local environment, and
3. To provide recommendations for materials selection based on the exposure conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Marine Studies and Exposure Stations in other Countries

Concrete technologists have been concerned with the performance of concrete in marine environments and research stations have been set up in several locations around the globe to study in detail the effects of such environment on concrete durability. Table 2.1 shows details of some marine research stations that have concentrated on studying the durability of concrete under a marine environment.

Table 2.1: Research Stations in Marine Environment around the World.

Exposure station	Location	Description of exposure station
Treat Island Exposure Station	In Cobscook Bay West port and Lubec, ME; USA. Specimens exposed since 1935.	Portland cements along with SCMs of about 65% GGBS or 25% Class F Fly Ash were used.
St. Augustine Exposure Station	Salt Run St. Augustine, Fla., USA; specimens exposed since 1940.	Max Temp =70 F Min Temp = -20 F
Buzzards Bay Exposure Station	Cape Cod Canal Sandwich Coast Guard Station, USA. Specimens exposed since 1938.	Max Temp =50 F Min Temp = 29 F
Field station at Mandapam CSIR- CENTRAL ELECTROCHEMICAL RESEARCH INSTITUTE	Karaikudi – 630 006, TAMIL NADU,India .	Field stations at Mandapam (Marine corrosion) and Tuticorin (Marine corrosion and fouling) – Corrosion map of India – Corrosion auditing.
Concrete Field Exposure Station in Norway	The Norwegian Building Research Institute 0314 OSLO, Norway	Exposure conditions include aggressive ground water, marine environment (submerged, splash zone and zone above seawater), and outdoor exposure in air.
Kuwait Institute for Scientific Research, Field Exposure Station	P.O. BOX: 24885 Kuwait - Safat 13109	Variety of environmental conditions, such as weathering exposure, on-shore, splash zone, tidal zone, buried, partially buried and submerged conditions.
Field exposure site, Khaleej Mardumah, Jubail, Saudi Arabia	Al-Jubail, Saudi Arabia	Exposure of concrete and metallic specimens to five exposure zones.

Research data collected over the years from these exposure stations have yielded significant results on the performance of concrete mixes and associated materials. In particular, the effect of various exposure zones (submerged, tidal, splash, atmospheric) on the performance of concrete was evaluated at these sites. Such research in exposure stations cannot be studied as reliably in the laboratory as in the field.

Details of studies carried out in some of the selected exposure sites are discussed in the following sub-sections.

2.1.1 Treat Island Exposure Station

Established in 1936, the US Army Corps of Engineers (USACE) Treat Island Marine Exposure Station is a natural weathering facility used to study concrete durability. It is Located on the Bay of Fundy near Eastport, Maine, the Treat Island exposure station naturally imposes a combination of severe environmental conditions on the exposed specimens. Specimens are located at mid-tide level and immersed in seawater twice daily. The facility can be visited only at select times because the tides vary by as much as 6.7 meters (22 feet). During the coldest part of the winter, temperatures average around -10ºC (15ºF). Depending on the specimen placement and severity of the winter, test specimens are subjected to anywhere from 100 to 160 freeze-thaw cycles per year. In addition, the cyclic flooding by saltwater and air drying subjects test specimens to chloride intrusion, wetting and drying, and abrasion/erosion.

There are approximately 22 active research programs underway (Refer to Table 2.2 below). Areas of investigation include: supplementary cementing materials (SCMs), high-performance concrete (HPC), lightweight concrete, fiber-reinforced concrete, roller-compacted concrete (RCC), prestressed concrete, polymer concrete, and concrete with high-range waterreducers.

Specimens are located on both the exposure rack (wharf) and on the beach adjacent to the rack. The concrete specimens are of variety of shapes and sizes, from concrete prisms to large cubes of concrete. Data are collected yearly and published biennially (ERDC, 2004).

Property of USACE, the Treat Island exposure station is directly maintained by the Engineering Research and Development Center (ERDC), Geotechnical and Structures Laboratory, Engineering Systems and Materials Division, Concrete and Materials Branch. Sponsors include: the Bureau of Reclamation, Department of Transportation,

CANMET, Degussa Admixtures, and Mobile Research and Development Corporation. Many other sponsors have specimens and ongoing programs on Treat Island. Although space at the marine exposure site is limited, specimens from outside organizations can be placed there provided that certain requirements are met (ERDC 2004).

2.1.2 St. Augustine Exposure Station

The effects of mild marine weathering are evaluated at Salt Bun, off Anastasia Island, near St. Augustine, Fla. The principal agent of attack at this installation is warm sea-water. The mean water temperature is about 70ºF. The average tide range is4.5 ft, with a maximum of 5.3 ft and a minimum of 3.7 ft. This station affords information on the effects of sea water on concrete specimens, apart from the effects of freezing and thawing. Companion specimens to those exposed at Treat Island in connection with a major investigation on Portland cements have been exposed here since 1940.

2.1.3 Buzzards Bay Exposure Station

The exposure station at Buzzards Bay was operated from 1938 through 1942. A total of 19 column specimens were exposed during this period in an investigation of blends of Portland cement with certain admixtures. The exposure rack was located in the Cape Cod Canal nearthe shore opposite the Sandwich Coast Guard Station. The average tidal fluctuation is 9 ft. The Portland Cement Association has experimental piling exposed here also for their long-time cement studies. Because of the presence of floating ice in the Cape Cod Canal during a considerable portion of the winter season and "because of the fact that the water temperature drops as low as 29ºF during the late winter, this station has been abandoned for installation of concrete specimens in favor of Treat Island.

2.1.4. Concrete Field Exposure Station in Norway

In 1936 researchers at the Technical University of Norway in Trondheim initiated a long termdurability study on the durability of concrete in an marine environment (Gjorv, 1971). Concrete specimens prepared with 313 kg/m^3 of total cementitious materials and a water/cement ratio of0.60 were cast into prisms having dimensions of 10 x 10 x 75 cm, cured for 48 hours and thenimmersed in Trondheim's harbour. Seven different cements with C_3A contents between 3and 13% were tested with and without trass (volcanic tuft - a

natural pozzolan) and slag;cement was substituted with 60% trass, and 20 and 40% slag. The concrete prisms were exposed to seawater that was never less than 1ºC for 30 years. Gjorv reported that the compressive strength of all the mixtures prepared with Portland cements having C_3A contents of 6, 9 and 10% were unaffected by seawater, but those with 11 and 13% C_3A exhibited sharp decline after 10 years of exposure. In contrast, all mixtures containing Portland cement (except for the mixture with 11% C_3A), exhibited a progressive decline in the flexural strength starting from the 15th year of exposure, regardless of the C_3A content. This appears to indicate an inconsistency between the compressive and flexural specimens, because flexural strength is generally affected more by most forms of deterioration than compressive strength. All four slag modified cements exhibited an increase in the compressive strength for the first 15 years; after 30 years of exposure two of the slag mixtures exhibited decrease in compressive and flexural strength. It is interesting to note that the latter slag cements had alumina (Al_2O_3) contents that were 42% lower than those that did not loose strength.

In two series of tests, concretespecimens with a cement content of 313 kg/m^3 and water/cement (w/c)ratios of 0.55, 0.60 and 0.65 and concretes with cement contents of 260, 313, 362 and 417kg/m^3 (w/c varied between 0.50 to 0.60) were evaluated with a Portland cement having a C_3A content of 13%. In general, the loss in compressive strength at 30 years of age decreasedas the w/c decreased and cement content increased. The best performance was obtained with a cement content of 417 kg/m^3. A similar pattern was observed with respect to trends inflexural strength.

In summary, the results reported by Gjorv (1971) demonstrate that the concretes with w/c between 0.50 and 0.65 have poor long term resistance to seawater attack, but that cementswith C_3A contents between 3 and 10% behaved similarly. Research by other workers (Malhotra and Bremner, 1996) clearly show the benefits of maintaining w/c below 0.45.

Table 2.2: Active Research Programs at Treat Island

Specimens on Exposure Rack	Areas of Investigation
Dickey Lincoln Dam (New England Division)	Specimens represent concrete mixtures to be used in Dickey Lincoln Dam
Lock Wall Repair Durability Program (REMR)	Evaluate methods and materials for bonding new concrete to existing concrete in repair of deteriorated lock walls
Kansas City District Aggregate Program	Provide field durability data on concrete specimens containing certain aggregate materials produced in the Kansas City District
Master Builders. Scaling, Corrosion Inhibitors and Concrete Freezing and Thawing Resistance *	Compliment other durability research efforts at laboratory on AEA, HRWA, corrosion-inhibiting admixtures, fly ash and silica fume.
CRREL/VTT Cooperative Study of Durability of High-Strength Concrete	Freeze-thaw durability of non-air-entrained concrete made with very fine mineral fillers.
Winfield Lock and Dam Freezing/Thawing Beams	Exterior mix design used at Winfield Lock Replacement, Kanawha County , West Virginia
Specimen Size - Frost Effects Investigation	Develop data on the effect of specimen size on the durability of concrete specimens in tidal exposure
Construction Engineering Research Laboratory Fibrous Concrete	Determine the effects of seawater and freeze-thaw action on flexural strength and other properties of various fiber concretes
Waterways Experiment Station Fibrous Concrete	Determine the effects of seawater and freeze- thaw action on the flexural strength and other properties of various fiber concretes.
Concrete-Polymer Materials	Investigate the durability and performance of polymer and polymer-impregnated concrete
CPAR - Modified Sulfur Concrete (Chempruf)	Investigate the durability of sulfur concrete (sulfur cement and fly ash are substituted for the portland cement-water paste).
CPAR - High-Performance Blended-Cement System (Pyrament)	Investigate durability of specimens of concrete made with Pyrament Blended Cement - Extended Setting Time (PBC-XT)
Charles River Dam - Smelt Brook Location Protection Project	Specimens represent concrete mixes that were used for the Charles River Dam, Boston , Mass. , and Smelt Brook Local Protection Project, Weymouth , Mass
Reactive Powder Concrete (RPC) in a Marine Environment	Study the effects of seawater on the corrosion of mild steel that was placed in RPC at different depths.
Roller-Compacted Concrete (RCC)	Two prototype RCC blocks (fabricated at WES) were evaluated for durability performance studies
Very High-Strength Concrete (VHSC)	Conduct freeze/thaw and seawater exposure studies on VHSC containing steel fiber reinforcement
Stewart Field Spheres	Determine if it was possible to evaluate changes in condition of concrete spheres by pulse velocity measurements
Natural Resources Canada - Durability of Concrete in Marine Environment *	Long-term performance of SCMs (low- and high-calcium fly ashes, pelletized and granulated blast-furnace slags, silica fume, rice-husk ash, and metakaolin) and lightweight aggregates in concrete.
Test Specimens on Beach	
Pre-stressed Concrete Program -	Exposure testing of end anchor ages and end-anchorage protection

Posttensioned Phase	for several types of post-tensioning
Quality Aggregate Investigation	Determine the durability of concrete containing aggregate larger than 1½ in. in size
Maximum Size of Coarse Aggregate Program	Compare the durability of concrete containing 6-in. max. Size aggregate to concrete containing 3-in. max. size aggregate
ExxonMobil - Hibernia Reference Cubes and Cylinders	Exposure testing of concrete cast from the production concrete used for the splash zone of the outer perimeter of Hibernia concrete offshore platform, Grand Banks, offshore Newfoundland
Thin Repair Concrete Slabs	Identify commercially available materials appropriate for thin repair of concrete surfaces
UNB Corrosion of Steel in Concrete	Conduct comparative corrosion durability studies on specimens containing both epoxy coated and uncoated steel reinforcing bars

2.2 Marine Studies and Exposure Stations in Gulf countries

2.2.1 Khaleej Mardumah Research Exposure Station

The concrete specimens examined under this research study were retrieved from the field exposure station "Khaleej Mardumah Research Station", established in Jubail Industrial City in 2000. The main purpose of this station is to gain practical knowledge on how to produce and protect concrete structures under natural and long-term exposure conditions. This field station is the first of its kind in the region. Exposure conditions include aggressive ground water, marine environment (submerged, splash zone and atmospheric), and outdoor exposure in air. The station involved casting different concrete specimens using different design and protection parameters including: cement type, water/cement ratio, pozzolanic additives, reinforcement type, water type, curing conditions, corrosion inhibitors, and concrete coatings. The prepared specimens are subjected to continuous monitoring for corrosion at predetermined intervals over long-term exposure. The setup and number of specimens have been designed for monitoring and testing for over 20 years.

Previous research indicates clearly the benefits that could be gained from the proper selection of cement and pozzolan types in marine structures. In order to maximize the benefits from these effects, the environmental conditions and the high salinity of the local seawater will be evaluated in this study and their beneficial effects on the performance of both plain and blended cements under the local marine conditions will be quantified.

Field exposure zones

The research field station, as shown in Figure 2.1, is divided into four zones representing the most aggressive and harsh conditions that prevail in the Arabian Gulf region and attack concrete structures. The details of the preparation and placement of the specimens in the field are described briefly below:

The tidal zone (Zone 1) represents one of the most aggressive conditions on the durability of concrete structures in the Arabian Gulf region. In this zone, the prepared concrete specimens are subjected to two cycles of wetting/drying per day due to high and low tides.

The splash zone (Zone 2) is considered to be the most critical marine exposure. In this zone, part of the surfaces of the prepared concrete specimens is located above seawater.

The partially Buried and Below Ground Zone (Zone 3) represents the actual exposure condition where most concrete structures, such as foundations and buried structures, are located and subjected to salt and sulfate contaminated ground water. This exposure causes the most widespread deterioration problems in concrete structures located along the coastal areas and in areas of high ground water.

The above ground zone (Zone 4) represents the atmospheric exposure zone along the coastal areas of the Arabian Gulf region. Reinforced concrete superstructures, which do not come in direct contact with the ground, are usually subjected to the atmosphere with high daily and seasonal variations in temperatures and humidity.

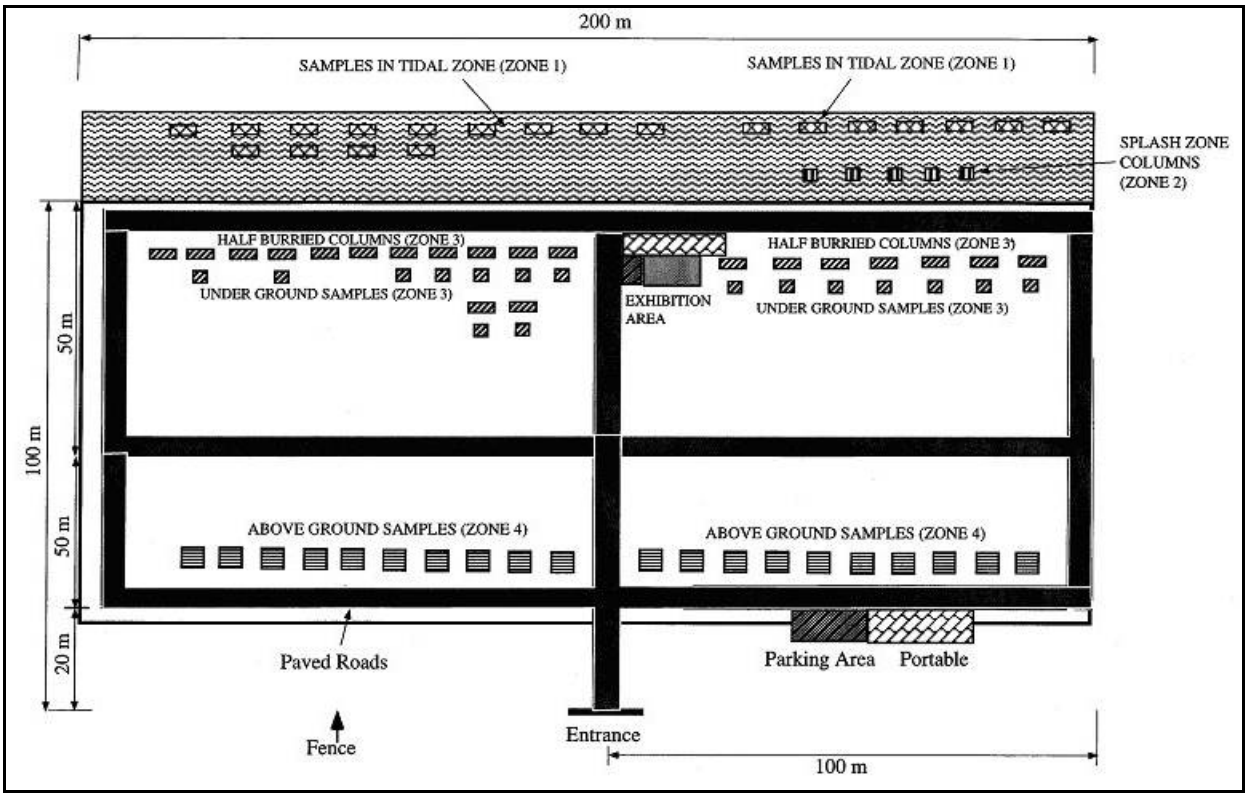


Figure 2.1. Sketch of the four exposure zones in the research field station.

2.2.2 Field Exposure Station at Kuwait Institute for Scientific Research

The Field Research Station is an exposure site erected at seafront location that provides a variety of environmental conditions, such as weathering exposure, on-shore, splash zone, tidal zone, buried and partially buried and submerged conditions. The Research Station supports long-term evaluations and assessments of high performance concrete and composite materials under the prevailing conditions of the Arabian Gulf Region. The main purpose of the Station is to collect data and information for use in the local building codes and standards. However, several attempts made by the author to retrieve the research data of the Station were not successful probably due to absence of any published data related to the concrete research performed in the station.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Materials

High-quality concrete specimens were cast as per RCJY specifications using the mixes detailed in Tables 3.1 through 3.4 for the tidal zone, splash zone, partially buried, below ground zone, and above ground zone, respectively.

The prepared concrete mixes cover a wide range of materials and variables. The control concrete mix used in this study is represented by mix J 25b according to RCJY specifications 03347. All the variables listed below were used with the control mix J 25b unless otherwise mentioned.

The following list contains all the materials and variables considered in the study:

- CEMENT TYPE: Types I and V.
- CEMENT CONTENT: Cementitious material contents were varied from 370 kg/m^3 to 450 kg/m^3.
- MIXING WATER TYPE: Potable water.
- W/C RATIO: Effective water to cementitious materials ratio of 0.40 was used for all mixes except mixes M4 where a 0.30 ratio was used.
- AGGREGATES: One type of both the fine aggregate (sand) and coarse aggregate were used in preparing all the concrete mixes.

REINFORCEMENT TYPE: Regular deformed steel reinforcement was used in reinforce concrete columns and beams.

POZZOLANIC ADMIXTURE: Silica fume (SF), Class F Fly ash (FA), Super-Pozz, and Ground Granulated Blast-furnace Slag (GGBS).

CURING

Wet burlap using potable water was used for curing the concrete specimens.

Table 3.1.Details of the mixes for the tidal zone (Zone 1).

Mix No.	Cement Type	Cement Content, kg	Water Type	W/C Ratio	Reinforcement	Additives, kg	Curing	Coating	Corrosion Inhibitors
Control TM1	I	370	Potable	0.40	Uncoated Steel	-	Normal	-	-
TM2	V	370	Potable	0.40	Uncoated Steel	-	-	-	-
TM3	I	450	Potable	0.40	Uncoated Steel	-	-	-	-
TM4	I	405	Potable	0.30	Uncoated Steel	36 SF	-	-	-
TM7	I	355	Potable	0.40	Uncoated Steel	30 SF	Normal	-	-
TM8	I	300	Potable	0.40	Uncoated Steel	70 FA	Normal	-	-
TM15	I	333	Potable	0.40	Uncoated Steel	37 Super-Pozz	Normal	-	-
TM17	I	265	Potable	0.40	Uncoated Steel	105 FA	Normal	-	-
TM20	I	114	Potable	0.40	Uncoated Steel	266 GGBS	Normal	-	-

Table 3.2.Detail of the mixes for the partially buried and below ground zone (Zone 3).

Mix No.	**Cement Type**	**Cement Content, kg**	**Water Type**	**W/C Ratio**	**Reinforcement**	**Additives, kg**	**Curing**	**Coating**	**Corrosion Inhibitors**
Control BM1	I	370	Potable	0.40	Uncoated Steel	-	Normal	-	-
BM2	V	370	Potable	0.40	Uncoated Steel	-	-	-	-
BM3	I	450	Potable	0.40	Uncoated Steel	-	-	-	-
BM4	I	405	Potable	0.30	Uncoated Steel	36 SF	-	-	-
BM7	I	355	Potable	0.40	Uncoated Steel	30 SF	Normal	-	-
BM8	I	300	Potable	0.40	Uncoated Steel	70 FA	Normal	-	-
BM15	I	333	Potable	0.40	Uncoated Steel	37 Super-Pozz	Normal	-	-
BM17	I	265	Potable	0.40	Uncoated Steel	105 FA	Normal	-	-
BM20	I	114	Potable	0.40	Uncoated Steel	266 GGBS	Normal	-	-

Table 3.3.Details of the mixes for the above ground zone (Zone 4).

Mix No.	**Cement type**	**Cement Content, kg**	**Water Type**	**W/C Ratio**	**Additives, kg**	**Curing**	**Coating**	**Corrosion Inhibitors**
Control AM1	I	370	Potable	0.40	-	Normal	-	-
AM2	V	370	Potable	0.40	-	-	-	-
AM3	I	450	Potable	0.40	-	-	-	-
AM4	I	405	Potable	0.30	36 SF	-	-	-
AM7	I	355	Potable	0.40	30 SF	Normal	-	-
AM8	I	300	Potable	0.40	70 FA	Normal	-	-
AM15	I	333	Potable	0.40	37 Super-Pozz	Normal	-	-
AM17	I	265	Potable	0.40	105 FA	Normal	-	-
AM20	I	114	Potable	0.40	266 GGBS	Normal	-	-

Table 3.4. Details of the mixes (non-reinforced specimens) for laboratory condition.

Mix No.	Cement type	Cement Content, kg	Water Type	W/C Ratio	Additives, kg	Curing
Control L1	I	370	Potable	0.40	-	Normal
L2	V	370	Potable	0.40	-	-
L3	I	450	Potable	0.40	-	-
L4	I	370	Potable	0.30	-	-
L7	I	355	Potable	0.40	30 SF	Normal
L8	I	300	Potable	0.40	70 FA	Normal
L15	I	333	Potable	0.40	37 Super-Pozz	Normal
L17	I	265	Potable	0.40	105 FA	Normal
L19	I	370	Potable	0.40	-	Reclaimed Water
L20	I	114	Potable	0.40	266 GGBS	Normal

The concrete specimens were exposed to the following zones:

- Tidal

- Aboveground
- Below ground

3.2 Specimen Preparation

To meet the objectives of the study, reinforced and unreinforced concrete specimens were prepared. Details of the specimens are described below.

3.2.1 Reinforced Concrete Specimens

Columns and beam specimen reinforced with normal deformed steel bars were prepared and placed at the exposure site for field monitoring as described below:

1. Columns with 35x35x300 cm dimensions for exposure in the partially buried zone (Zone 3). The reinforced columns were utilized for visual observations and corrosion monitoring. In addition, core specimens were obtained from the columns in the below ground and on the ground zone to determine the chloride, sulfate, and alkalinity (OH^-) profile and depth of carbonation, respectively.
2. Beam specimens with 25x30x75 cm dimensions were exposed in the tidal zone. Reinforced beams were used for visual observation and corrosion monitoring. In addition, core samples were obtained to determine chloride, sulfate, and alkalinity (OH^-) profiles, and to determine the depth of carbonation.

3.2.2 Unreinforced Concrete Specimens

1. Cubes with 15x15x15 cm dimensions were placed in the tidal zone (Zone 1), below ground zone (Zone 3) and above ground zone (Zone 4). Cube specimens were used to determine the water permeability.
2. Cylinders, measuring 7.5 cm in diameter and 15 cm high were placed in the tidal zone (Zone 1), below ground zone (Zone 3) and above ground zone (Zone 4). The cylindrical specimens were used to determine chloride permeability, electrical resistivity, water absorption, compressive strength, and sulfate resistance.

The above specimens were placed in the exposure zones as described in Tables 3.5 through 3.8.

Table 3.5. Number of specimens conditioned in the laboratory.

Mix #	Concrete description	Cylinders	Cubes
Control LM1	J 25 b without Pozzolanic admixtures	12	6
LM2	J 25 b with type V cement	12	6
LM3	J 35 without admixtures	12	6
LM4	J 35 with 8% SF and w/c = 0.30	12	6
LM7	J 25 b with 8 % cement replacement with SF	12	6
LM8	J 25 b with 20 % cement replacement with FA	12	6
LM15	J 25 b with 10 % cement replacement with Superpozz	12	6
LM17	J 25 b with 30 % cement replacement with FA	12	6
LM20	J 25 b with 70 % cement replacement with GGBS	12	6
Total		**108**	**54**

Table 3.6.Number of specimens placed in the Tidal zone (Zone 1).

Mix #	Concrete description	Beams	Cylinders	Cubes
TM1	J 25 b without Pozzolanic admixtures	3	49	24
TM2	J 25 b with type V cement	3	49	24
TM3	J 35 without admixtures	3	49	24
TM4	J 35 with 8% SF and w/c = 0.30	3	49	24
TM7	J 25 b with 8 % cement replacement with SF	3	49	24
TM8	J 25 b with 20 % cement replacement with FA	3	49	24
TM15	J 25 b with 10 % cement replacement with Super-Pozz	3	49	24
TM17	J 25 b with 30 % cement replacement with FA	3	49	24
TM20	J 25 b with 70 % cement replacement with GGBS	3	49	24
Total		**27**	**441**	**216**

Table 3.7.Number of specimens placed in the partially buried zone (Zone 3).

Mix #	Concrete description	Columns	Cylinders	Cubes
BM1	J 25 b without Pozzolanic admixtures	3	49	24
BM2	J 25 b with type V cement	3	49	24
BM3	J 35 without admixtures	3	49	24
BM4	J 35 with 8% SF and w/c = 0.30	3	49	24
BM7	ɲ ₊ 愀扪摧viii十ɡh 8 % cement replacement	3	49	24
BM8	J 25 b with 20 % cement replacement with FA	3	49	24
BM15	J 25 b with 10 % cement replacement with Superpozz	3	49	24
BM17	J 25 b with 30 % cement replacement with FA	3	49	24
BM20	J 25 b with 70% cement replacement with GGBS	3	49	24
Total		**27**	**441**	**216**

Table 3.8. Number of specimens in the above ground zone(Zone 4).

Mix #	Concrete description	Cylinders	Cubes
Control AM1	J 25 b without Pozzolanic admixtures	49	24
AM2	J 25 b with type V cement	49	24
AM3	J 35 without admixtures	49	24
AM4	J 35 with 8% SF and w/c = 0.30	49	24
AM7	J 25 b with 8 % cement replacement with SF	49	24
AM8	J 25 b with 20 % cement replacement with FA	49	24
AM15	J 25 b with 10 % cement replacement with Superpozz	49	24
AM17	J 25 b with 30 % cement replacement with FA	49	24
AM20	J 25 b with 70 % cement replacement with GGBS	49	24
Total		**441**	**216**

3.3 Test Methods

Several tests were conducted on the concrete specimens after 10 years of exposure. The field specimens were visually observed for signs of deterioration and corrosion potentials were measured. After 10 years of exposure, the moulded and core specimens were retrieved for testing and analysis in the laboratory.

3.3.1 Visual Observation in the Field

All the exposed specimens were monitored and observed for any noticeable signs of deterioration. The visual observations were noted using the forms developed for this purpose and photographs of the specimens were also taken.

The corrosion potentials on steel in the reinforced columns and beams placed in zones 1, 2, and 3 were measured according to ASTM C 876. Corrosion potential measurements are used to estimate the likelihood of reinforcement corrosion. Generally, accepted values representing corroding and non-corroding conditions, as given by ASTM C 876 are as follows:

a. If the potentials over an area are more positive than -200 mV, against copper-copper sulfate electrode (CSE), then there is a more than 90% probability that no reinforcing steel corrosion is occurring.

b. If the potentials over an area are in the range of -200 to -350 mV against CSE, corrosion of reinforcing steel in that area is uncertain.

c. If the potentials over an area are more negative than -350 mV against CSE, then there is a greater than 90% probability that reinforcement corrosion is occurring in that area.

The corrosion potential survey was conducted using a copper-copper sulfate reference electrode (CSE) and a high impedance voltmeter. The locations of the corrosion potential readings were determined using an iron depth meter and are shown in Figures 3.1 through 3.3 specimen placed in zones 1, 2, and 3, respectively.

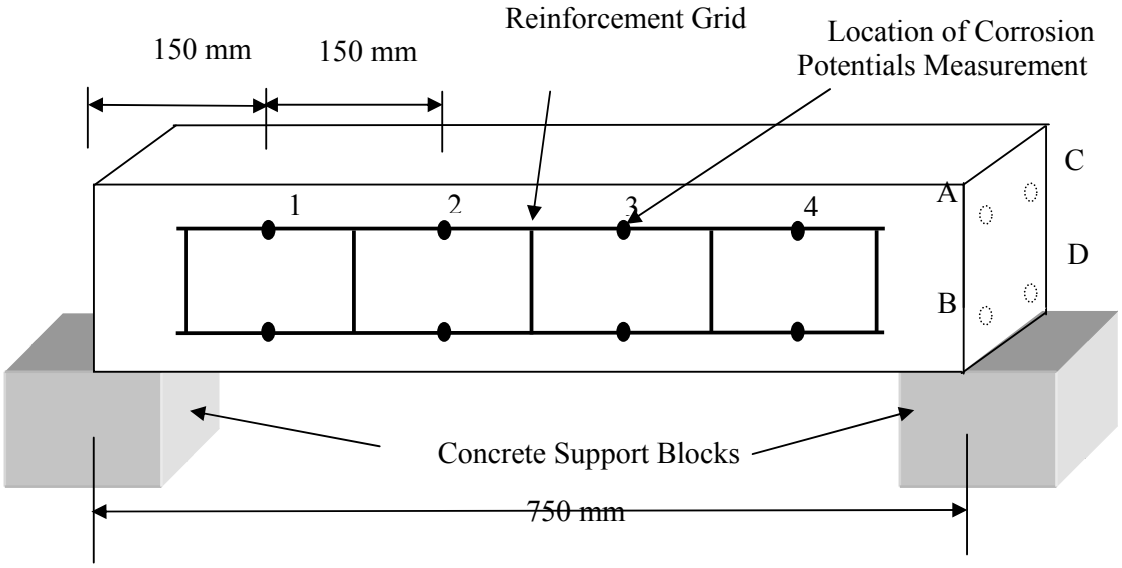


Figure 3.1. Locations of corrosion potential readings for a beam specimen in tidal zone(Zone 1).

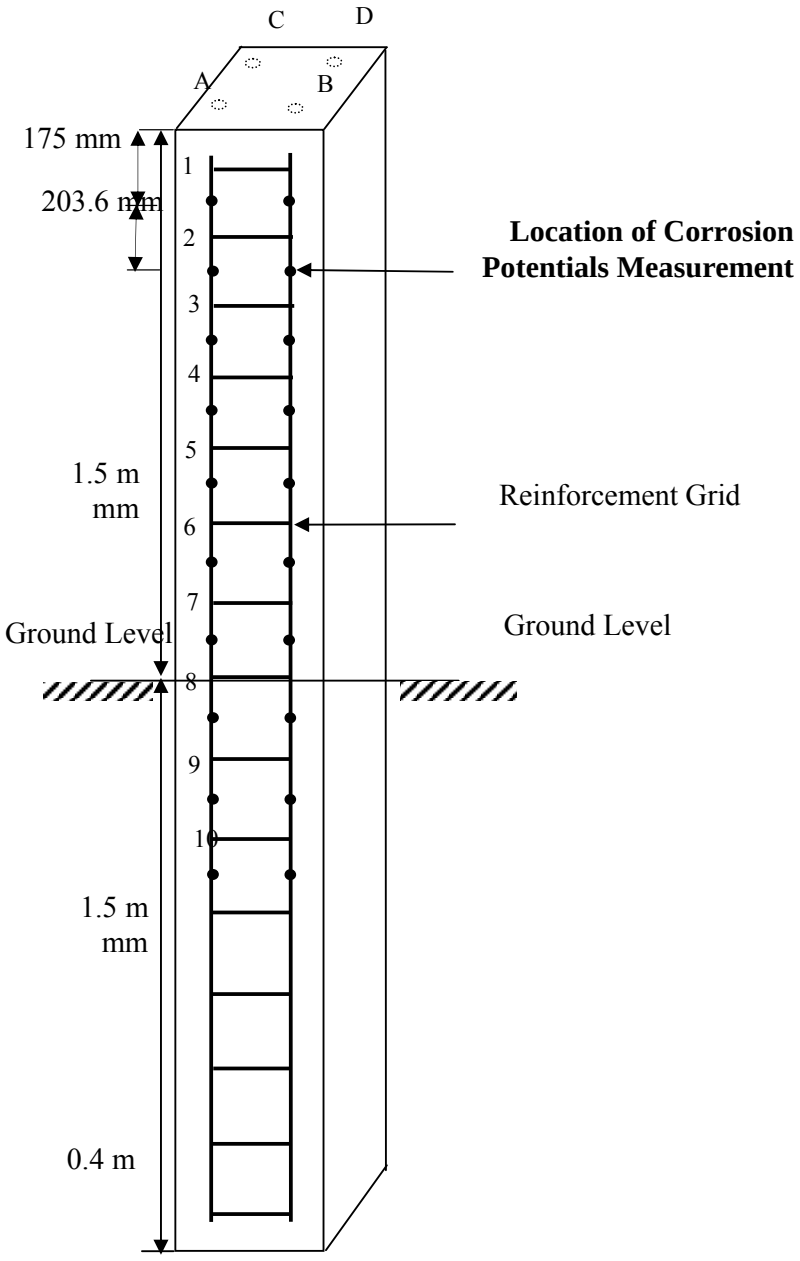


Figure 3.2. Locations of corrosion potential readings for a column specimen in partially buried zone (Zone 3).

3.3.2. Laboratory Tests

The specimens retrieved from the field were tested to evaluate the following properties:

i. Chloride, Sulfate, and Alkalinity (OH^-) Profiles

ii. Water Permeability

iii. Chloride Permeability

iv. Electrical Resistivity

v. Water Absorption

vi. Compressive Strength

vii. Depth of Carbonation

viii. Morphology and mineral composition by SEM and XRD, respectively.

Table 3.9 details the number of specimens utilized in the test program while Table 3.10 details the tests.

Table 3.9. Number of specimens used in each test.

Test type	No. of specimens+
1. Visual observation, and Corrosion monitoring ASTM C 876	9(m) x 1(*BAZ*) X 3(s) = 27 columns 9(m) x 1(TZ) x 3(s) = 27 beams
2. Cl^-, SO_4^{--} and OH^- content(same specimens as in1.)	9(m) x 1(*BAZ*) X 1(s) = 9 columns 9(m) x 1(*TZ*) X 1(s) = 9 beams
3. Electrical Resistivity (cylinders)	9(m) x 3(e) X 1(p) X 3(s) = 81
4. Water permeability (cubes)DIN 1048	9(m) x 3(e) X 1(p) X 3(s) = 81
5. Water absorption (cylinders)ASTM C 642	Using the electrical resistivity specimens
6. Chloride permeability (cylinders)ASTM C 1202	9(m) x 3(e) X 1(p) X 1(s) = 27
7. Compressive strength (cylinders)ASTM C 39	9(m) x 3(e) X 1(p) X 3(s) = 81
9. Carbonation	Using cores from columns and beams
Total	27 columns 27 beams 81 cubes 189 cylinders

+ BAZ - Below and above ground; TZ - Tidal zone; TSZ- Tidal (splash) zone;m - no. of mixes; s - no. of specimens; e - no. of exposures; p - no. of periods.

Table 3.10. Number of tests conducted.

Test type	No. of tests+
1. Corrosion monitoring (columns) Corrosion monitoring (beams)	9(m) x 3(s) x1(p) = 27 9(m) x3(s) x1(p) = 27
2. Cl^-, SO_4^{--}, and OH^- contents (cores)	9(m) x 1(BAZ) x 1(p) x 2(c) = 18 9(m) x 1(TZ) x 1(p) x 1(c) = 9
3. Electrical resistivity (cylinders)	9(m) x 3(e) x 1(p) x 3(s) = 81
4. Water absorption (cylinders)	9(m) x 3(e) x 1(p) x 3(s) = 81
3. Water permeability (cubes)	9(m) x 3(e) x 1(p) x 3(s) = 81
4. Chloride permeability (cylinders)	9(m) x 3(e) x 1(p) x 3(s) = 81
5. Compressive strength (cylinders)	9(m) x 3(e) x 1(p) x 3(s) = 81
6. Sulfate resistance (cylinders)	9(m) x 3(e) x 1(p) x 3(s) = 81
7. Carbonation (cylinders)	9(m) x 3(e) x 1(p) x 3(s) = 81

+ m - no. of mixes; BAZ - Below and above ground; TZ - Tidal zone; s - no. of specimens and samples; e - no. of exposures; p - no. of periods; c - cores.

The experimental data were analysed to assess the relative performance of the selected cement types under the local marine environment.

CHAPTER 4

RESULTS AND DISSCUSSION

4.1. Specimens Exposed to Tidal Zone

4.1.1 Visual observation in field

BEAMS

No noticeable deterioration was noted in the beam specimens exposed in the tidal zone for 10 years, except for mix TM20. However, deposition of algae was noticed in almost all the specimens due to which the color of concrete changed to greenish black to black in some cases. Minor to major deposits of shells were noticed on the specimens with high density of shells found on the side facing the sea. Shell deposits were not noted on the top face of the beam specimens. Moderate deterioration was noted at the corners of the beams of mix TM20. A typical photograph of a beam specimen is shown in Figure 4.1.

Figure 4.1. Typical photograph of a beam specimen in the tidal zone.

CYLINDERS

There was moderate deterioration of cylindrical concrete specimens of mix TM20 and minor deterioration was noted in the specimens of TM7, and TM8. Negligible to minor deposits of shells were noticed mostly in the void spaces on the surface of the specimens. Greenish

deposits of algae were also observed mostly on the flat and circular surface of the cylindrical specimens. All the specimens exhibited minor erosion especially on the edges due to movement of the specimen under wave action on the concrete pedestal. The corners of some of the specimens were broken probably due to rolling action of the seawater. The color of the specimens changed to greenish black due to the algae deposit. Photograph of atypical specimen is shown in Figure 4.2.

CUBE SPECIMENS

There was moderate deterioration of cube specimens of mix TM20 and TM8. Minor to major deposits of shells were noticed on the surface of the specimen. The corners of some of the specimens were broken due to rolling action by the sea water. Greenish deposits of algae and probably oil were also observed. This may have caused discoloration of the specimen. Photograph of a typical specimen is shown in Figure 4.3.

Figure 4.2. Typical concrete cylindrical specimen exposed to tidal zone.

Figure 4.3. Typical cube concrete specimen exposed to the tidal zone.

4.1.2 Monitoring Corrosion Potentials in the Field

The corrosion potentials in mixes TM1 (Type I cement) and TM2 (Type V cement), were more than -350 mV CSE indicating uncertain corrosion state. In TM3, beam with high cement content, the corrosion potential readings remained below -350 mV indicating uncertain corrosion state in the beam. As compared to the potential values in specimens TM1 and TM2, the potentials in TM3 are more in no corrosion range. This could be attributed to the beneficial effect of high cement content in TM3 concrete which was 450 kg/m^3. Similarly, the potential values indicated a state of uncertain corrosion in specimen TM4, beam with low w/c ratio.

In mix TM4, beam with low w/c ratio, the corrosion potential was more than -350mV CSE indicating 90% probability of active corrosion.

In mix TM8 (20% FA) the potential value was -422 mV SCE. Similarly, in mix TM17 (30% FA) the potential value was -273 mV SCE. The potential value in mixTM15 (10% Superpozz) was -218 mV SCE indicating uncertain corrosion state.

In specimen TM20, beam with GGBS, remained below -350 mV SCE indicating uncertain corrosion state.

Table 4.1. Corrosion potential on steel in the beam specimen TM1–1, exposed in tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-242	-238	-241	-246
B	-242	-241	-241	-243
C	-230	-226	-228	-232
D	-230	-224	-227	-233

Table 4.2. Corrosion potentials on steel in the beam specimen TM1–2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-413	-420	-427	-435
B	-421	-424	-430	-435
C	-450	-449	-454	-455
D	-450	-448	-452	-454

Table 4.3. Corrosion potential on steel in beam specimen TM1–3, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-240	-240	-241	-250
B	-237	-238	-240	-241
C	-242	-242	-245	-244
D	-240	-240	-240	-242

Table 4.4. Corrosion potential on steel in the beam specimen TM2–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-340	-335	-340	-350
B	-345	-340	-345	-350
C	-330	-330	-335	-335
D	-335	-335	-335	-335

Table 4.5. Corrosion potentials on steel in the beam specimen TM2–2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-340	-345	-330	-332
B	-335	-338	-335	-335
C	-280	-277	-275	-269
D	-280	-275	-275	-268

Table 4.6. Corrosion potential on steel in the beam specimen TM2–3, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-285	-280	-280	-275
B	-285	-285	-280	-277
C	-295	-295	-300	-305
D	-295	-294	-300	-300

Table 4.7. Corrosion potentials on steel in the specimen TM3–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A				
B				
C				
D				

Table 4.8. Corrosion potential on steel in the beam specimen TM3–2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-240	-238	-236	-236
B	-239	-238	-238	-238
C	-238	-240	-242	-244
D	-236	-236	-240	-240

Table 4.9. Corrosion potentials on steel in the beam specimen TM3–3, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-182	-180	-182	-185
B	-180	-180	-185	-185
C	-190	-190	-191	-192
D	-188	-188	-190	-190

Table 4.10. Corrosion potentials on steel in the beam specimen TM4–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-227	-225	-230	-235
B	-230	-230	-230	-235
C	-225	-222	-222	-230
D	-225	-225	-225	-225

Table 4.11. Corrosion potentials on steel in the beam specimen TM4–2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-221	-218	-220	-220
B	-220	-219	-220	-222
C	-220	-290	-225	-232
D	-222	-220	-225	-225

Table 4.12.Corrosion potentials on steel in the beam specimen TM4– 3, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-195	-190	-190	-190
B	-195	-190	-190	-190
C	-195	-192	-192	-195
D	-192	-190	-190	-190

Table 4.13. Corrosion potentials on steel in the beam specimen TM7–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-440	-440	-465	-550
B	-450	-455	-470	-530
C	-455	-450	-455	-460
D	-455	-450	-455	-465

Table 4.14. Corrosion potentials on steel in the beam specimen TM7–2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-445	-445	-440	-440
B	-445	-440	-440	-440
C	-425	-420	-420	-425
D	-425	-420	-420	-425

Table 4.15. Corrosion potentials on steel in the beam specimen TM7–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-210	-205	-205	-200
B	-210	-209	-205	-205
C	-200	-200	-195	-195
D	-200	-195	-195	-195

Table 4.16. Corrosion potentials on steel in the beam specimen TM8–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	Wire broken			
B				
C				
D				

Table 4.17. Corrosion potentials on steel in the beam specimen TM8–2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-385	-366	-365	-360
B	-365	-365	-365	-360
C	-335	-335	-335	-340
D	-335	-337	-335	-340

Table 4.18. Corrosion potentials on steel in the beam specimen TM8–3, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	Wire broken			
B				
C				
D				

Table 4.19. Corrosion potentials on steel in the beam specimen TM15–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-235	-235	-230	-235
B	-235	-235	-235	-235
C	-245	-245	-245	-240
D	-245	-243	-245	-240

Table 4.20. Corrosion potentials on steel in the beam specimen TM15–2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-245	-245	-240	-240
B	-242	-242	-245	-240
C	-240	-235	-240	-235
D	-245	-250	-245	-240

Table 4.21. Corrosion potentials on steel in the beam specimen TM15–3, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-180	-175	-177	-170
B	-180	-175	-175	-170
C	-170	-170	-170	-170
D	-170	-170	-175	-175

Table 4.22. Corrosion potentials on steel in the beam specimen TM17–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-296	-295	-294	-297
B	-293	-294	-293	-294
C	-294	-294	-294	-292
D	-291	-291	-292	-292

Table 4.23. Corrosion potentials on steel in the beam specimen TM17–2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-300	-305	-300	-305
B	-298	-300	-300	-300
C	-300	-305	-310	-305
D	-300	-307	-305	-305

Table 4.24. Corrosion potentials on steel in the beam specimen TM17–3, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-225	-225	-225	-225
B	-225	-220	-222	-225
C	-225	-225	-225	-224
D	-222	-225	-225	-222

Table 4.25. Corrosion potentials on steel in the beam specimen TM20–1, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-460	-468	-470	-475
B	-460	-466	-470	-470
C	-475	-476	-475	-480
D	-475	-475	-475	-480

Table 4.26. Corrosion potentials on steel in the beam specimen TM20-2, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-135	-133	-135	-135
B	-135	-135	-133	-135
C	-210	-205	-215	-225
D	-215	-205	-210	-225

Table 4.27. Corrosion potentials on steel in the beam specimen TM20–3, exposed in the tidal zone.

Corrosion Potentials at Co-ordinates, mV CSE				
	1	2	3	4
A	-155	-155	-160	-170
B	-155	-160	-160	-165
C	-162	-170	-175	-180
D	-162	-170	-175	-180

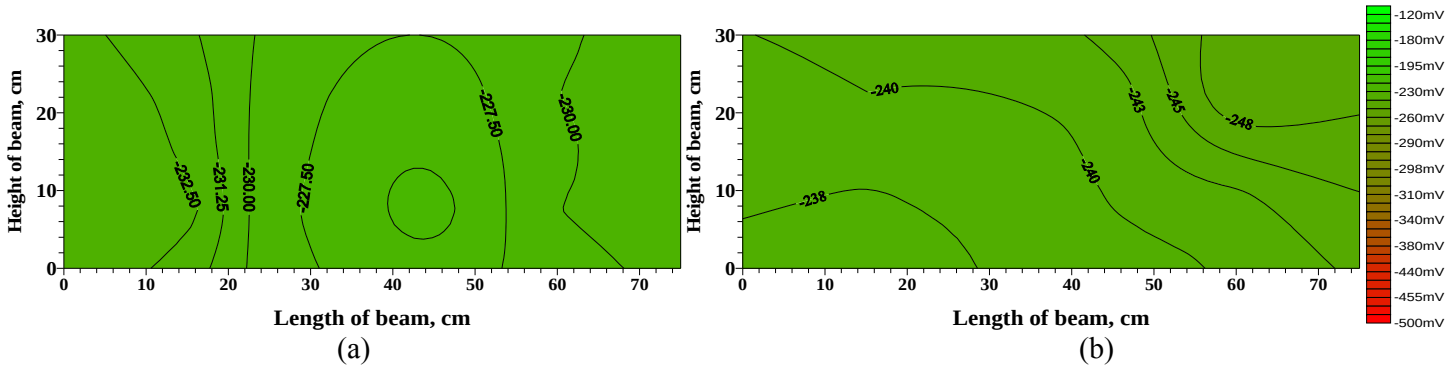


Figure 4.4.Corrosion potential contours in beam specimen TM1-1 exposed in the tidal zone (a) facing inland (b) facing sea.

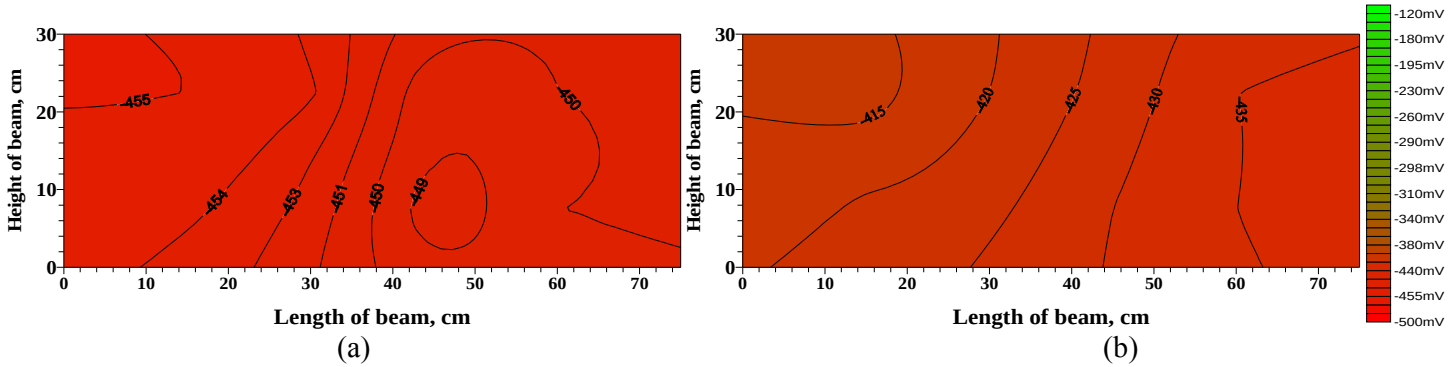


Figure 4.5.Corrosion potential contours in beam specimen TM1-2 exposed in the tidal zone (a) facing inland (b) facing sea.

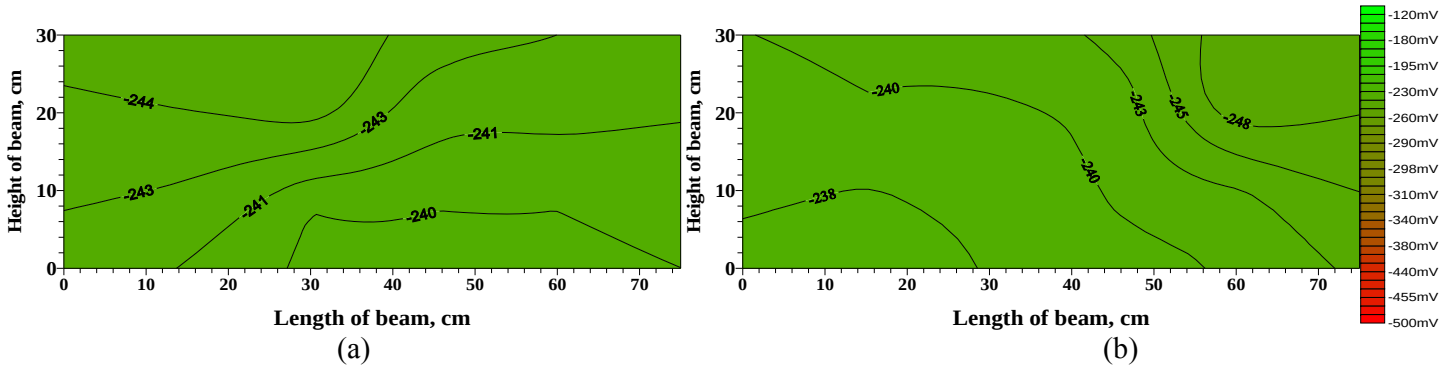


Figure 4.6.Corrosion potential contours in beam specimen TM1-3 exposed in the tidal zone (a) facing inland (b) facing sea.

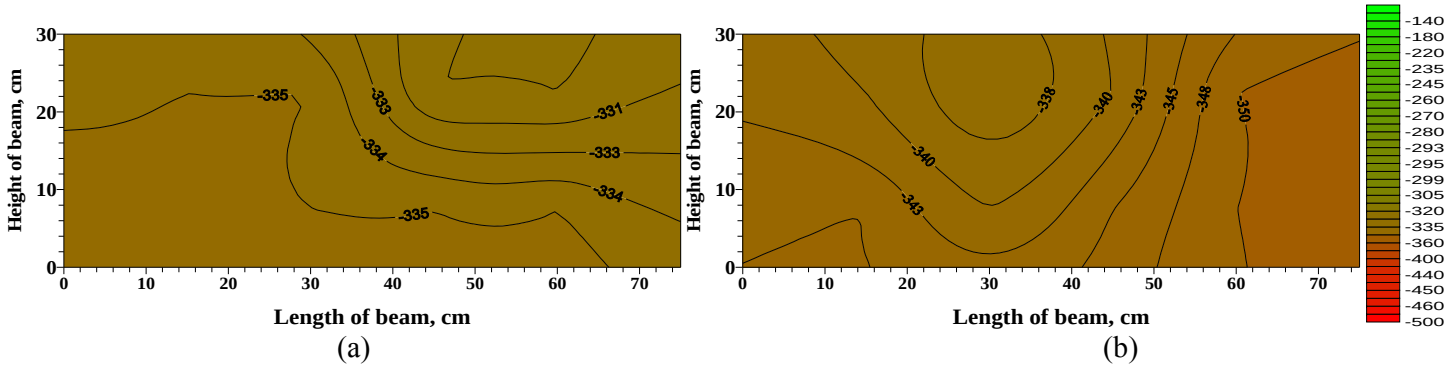
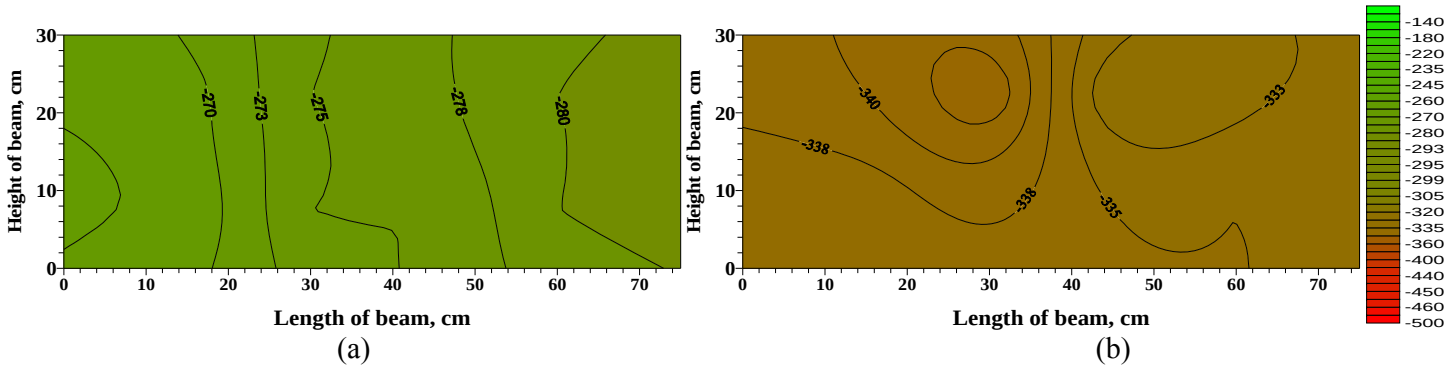
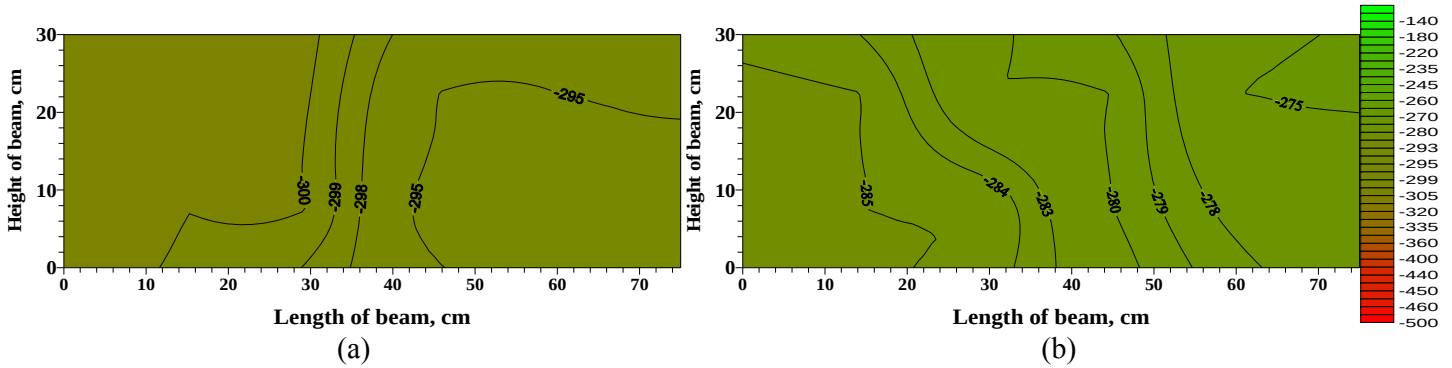


Figure 4.7.Corrosion potential contours in beam specimen TM2-1 exposed in the tidal zone (a) facing inland (b) facing sea.



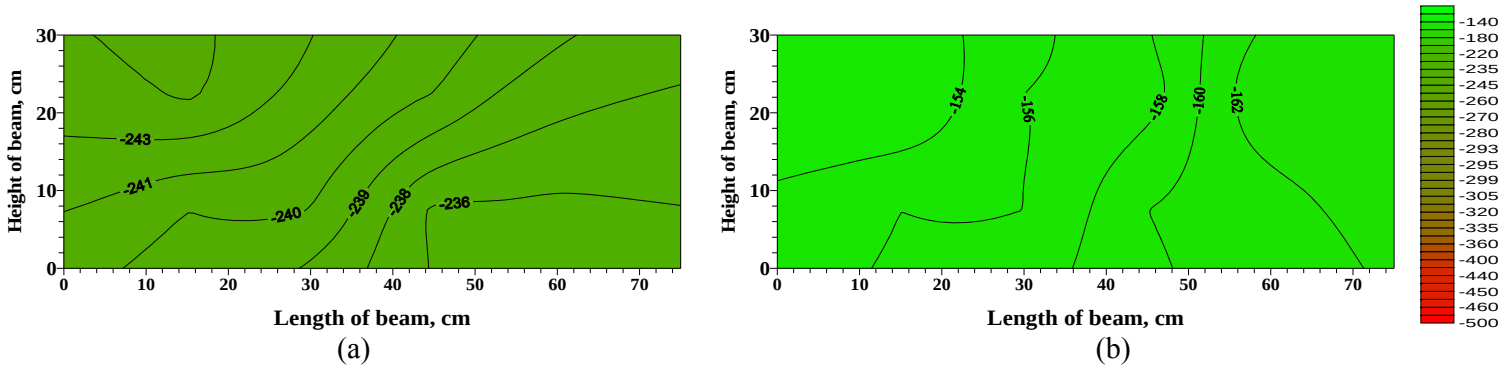
(a) (b)

Figure 4.8.Corrosion potential contours in beam specimen TM2-2 exposed in the tidal zone (a) facing inland (b) facing sea.



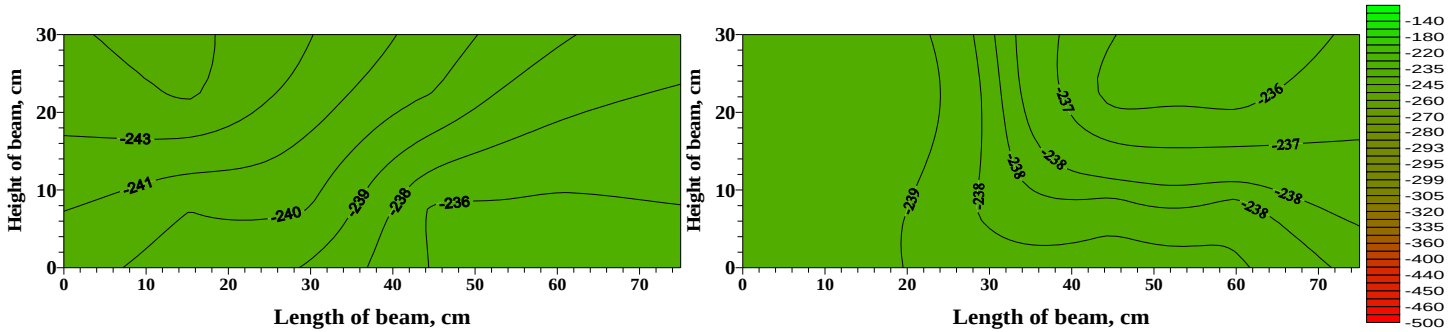
(a) (b)

Figure 4.9. Corrosion potential contours in beam specimen TM2-3 exposed in the tidal zone (a) facing inland (b) facing sea.



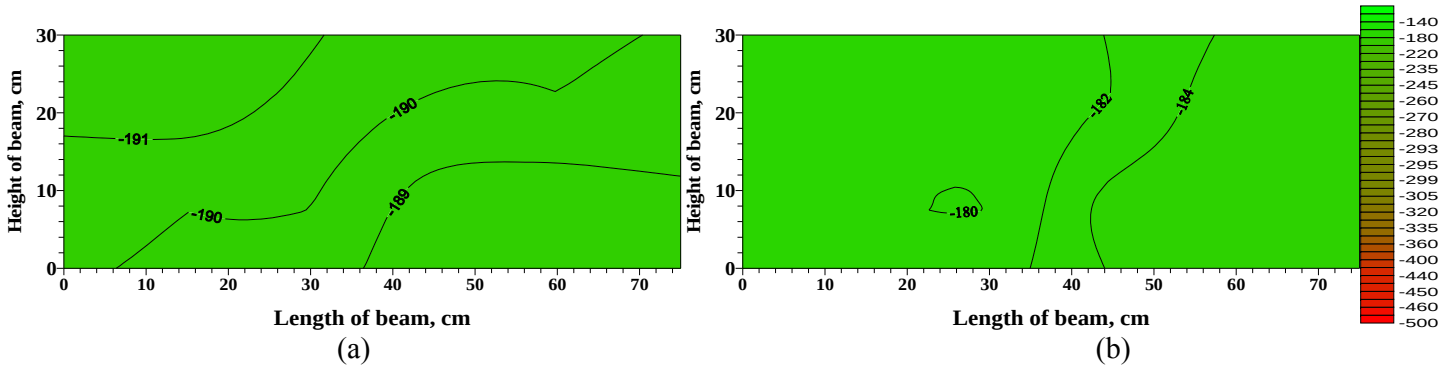
(a) (b)

Figure 4.10. Corrosion potential contours in beam specimen TM3-1 exposed in the tidal zone (a) facing inland (b) facing sea.



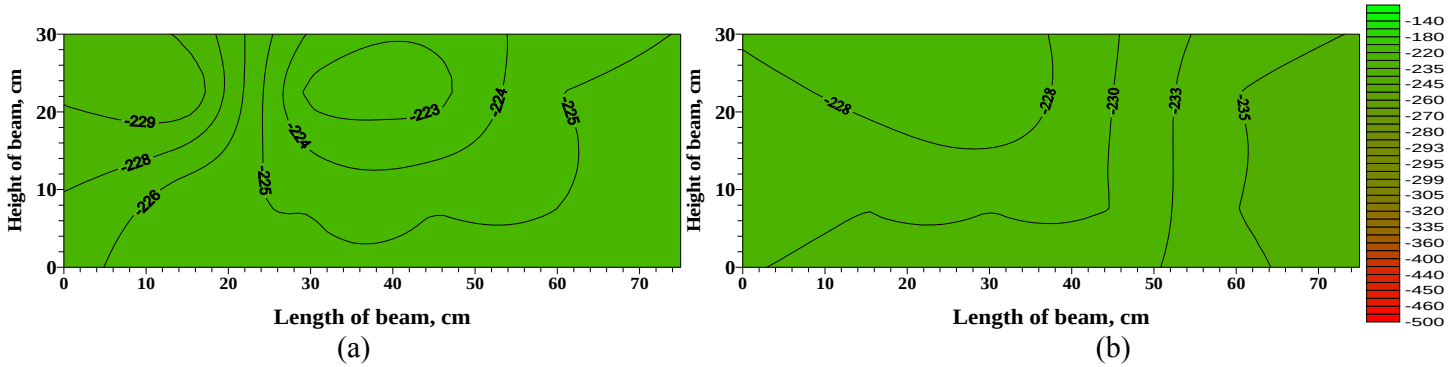
(a) (b)

Figure 4.11.Corrosion potential contours in beam specimen TM3-2 exposed in the tidal zone (a) facing inland (b) facing sea.



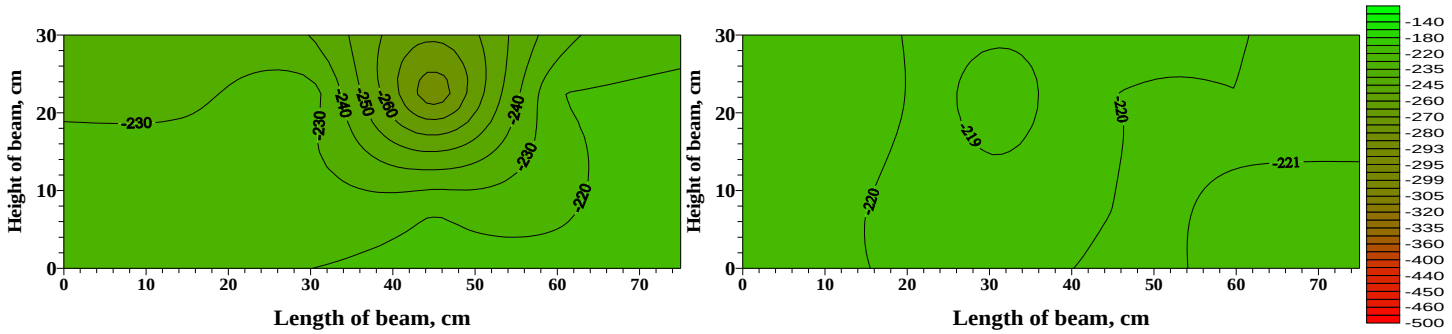
(a) (b)

Figure 4.12.Corrosion potential contours in beam specimen TM3-3 exposed in the tidal zone (a) facing inland (b) facing sea.



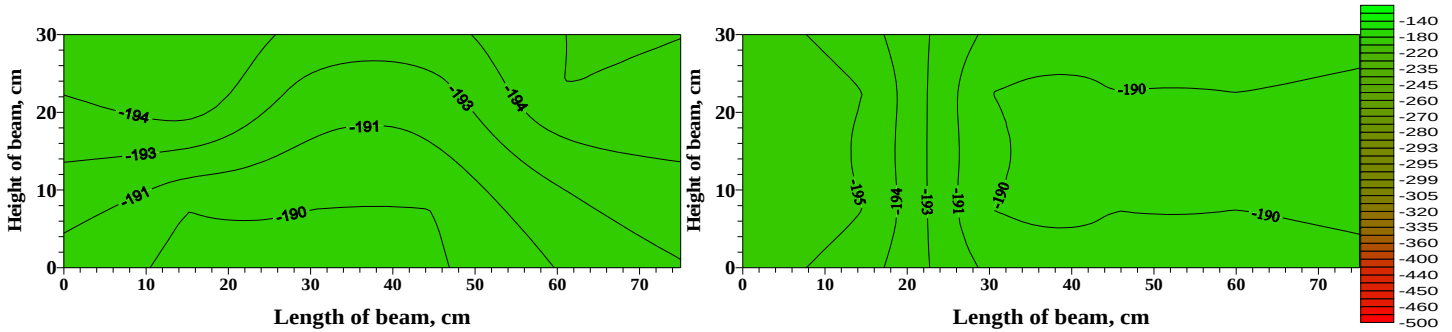
(a) (b)

Figure 4.13. Corrosion potential contours in beam specimen TM4-1 exposed in the tidal zone (a) facing inland (b) facing sea.



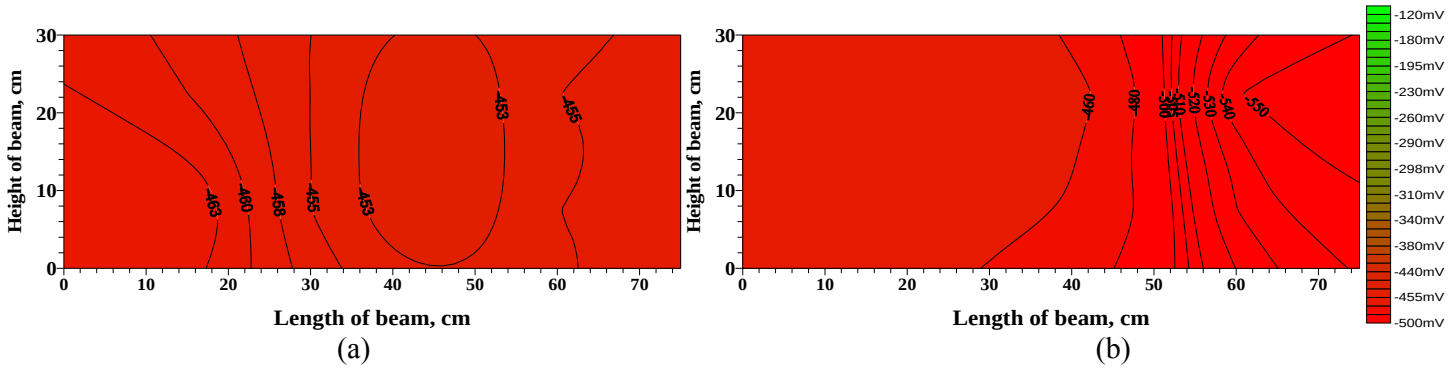
(a) (b)

Figure 4.14. Corrosion potential contours in beam specimen TM4-2 exposed in the tidal zone (a) facing inland (b) facing sea.



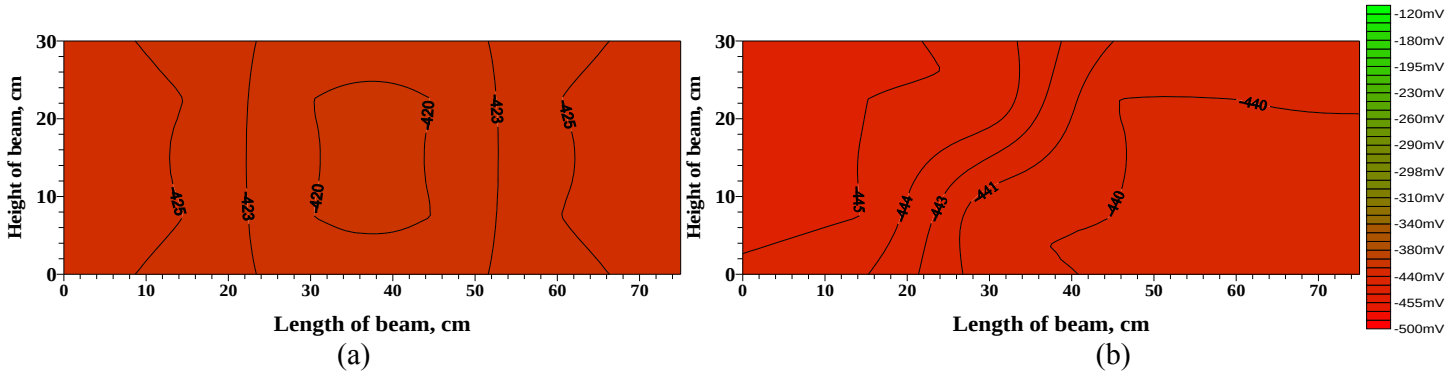
(a) (b)

Figure 4.15. Corrosion potential contours in beam specimen TM4-3 exposed in the tidal zone (a) facing inland (b) facing sea.



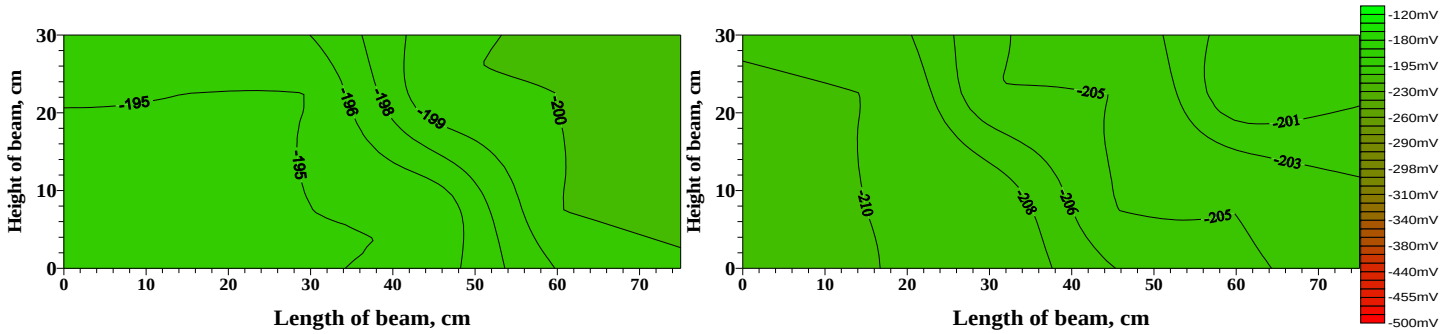
(a) (b)

Figure 4.16. Corrosion potential contours in beam specimen TM7-1 exposed in the tidal zone (a) facing inland (b) facing sea.



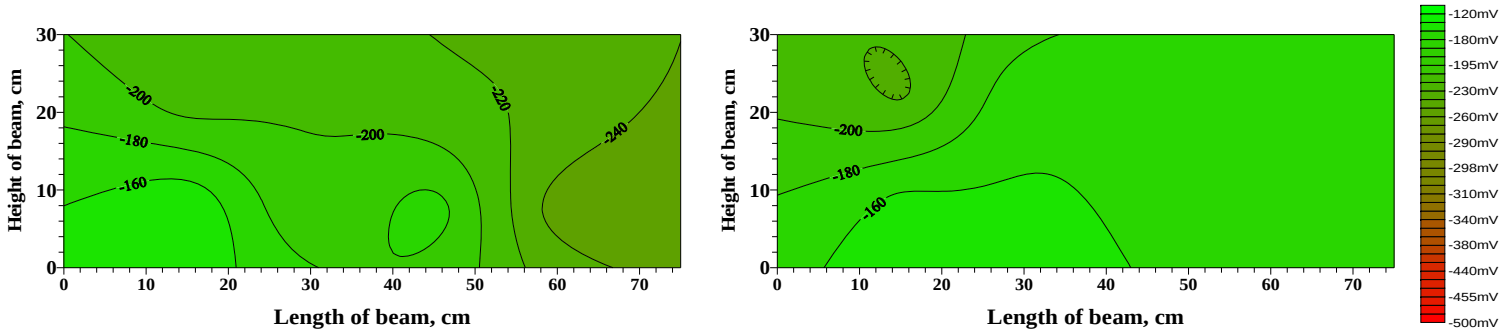
(a) (b)

Figure 4.17. Corrosion potential contours in beam specimen TM7-2 exposed in the tidal zone (a) facing inland (b) facing sea.



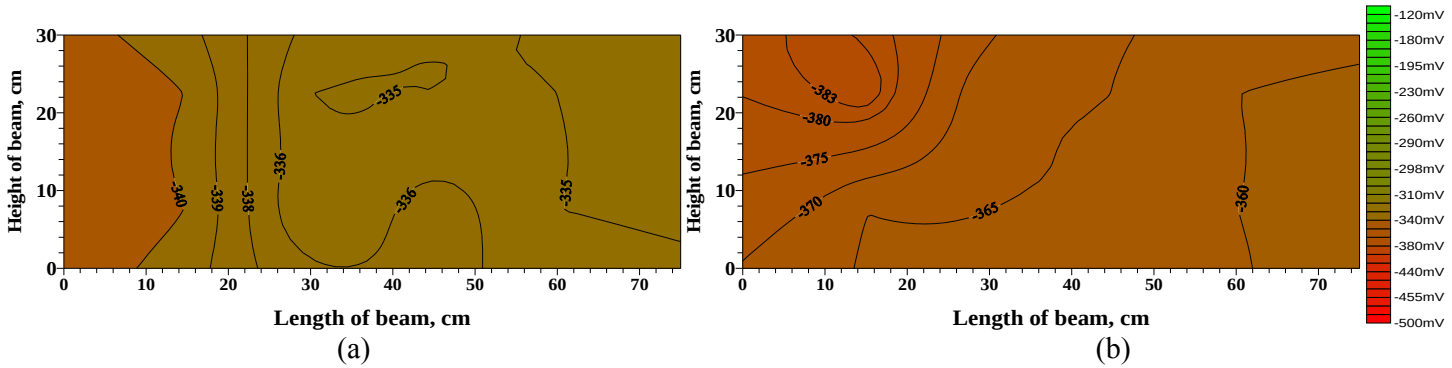
(a) (b)

Figure 4.18. Corrosion potential contours in beam specimen TM7-3 exposed in the tidal zone (a) facing inland (b) facing sea



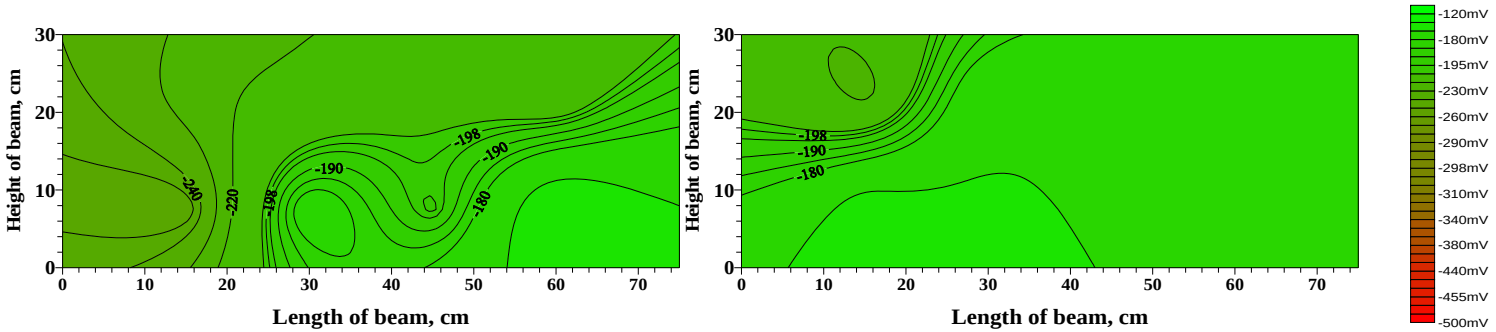
(a) (b)

Figure 4.19. Corrosion potential contours in beam specimen TM8-1 exposed in the tidal zone (a) facing inland (b) facing sea.



(a) (b)

Figure 4.20. Corrosion potential contours in beam specimen TM8-2 exposed in the tidal zone (a) facing inland (b) facing sea.



(a) (b)

Figure 4.21. Corrosion potential contours in beam specimen TM8-3 exposed in the tidal zone (a) facing inland (b) facing sea.

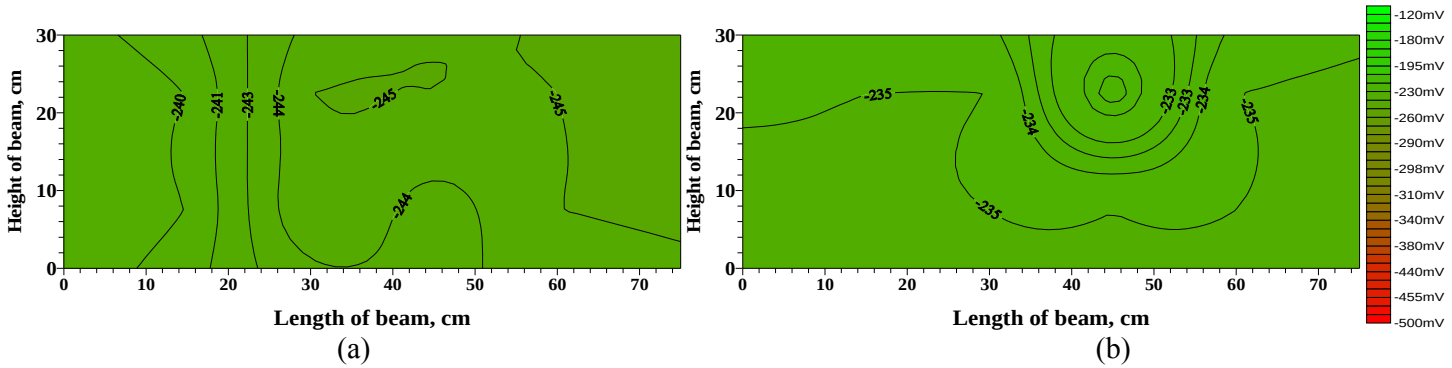


Figure 4.22. Corrosion potential contours in beam specimen TM15-1 exposed in the tidal zone (a) facing inland (b) facing sea.

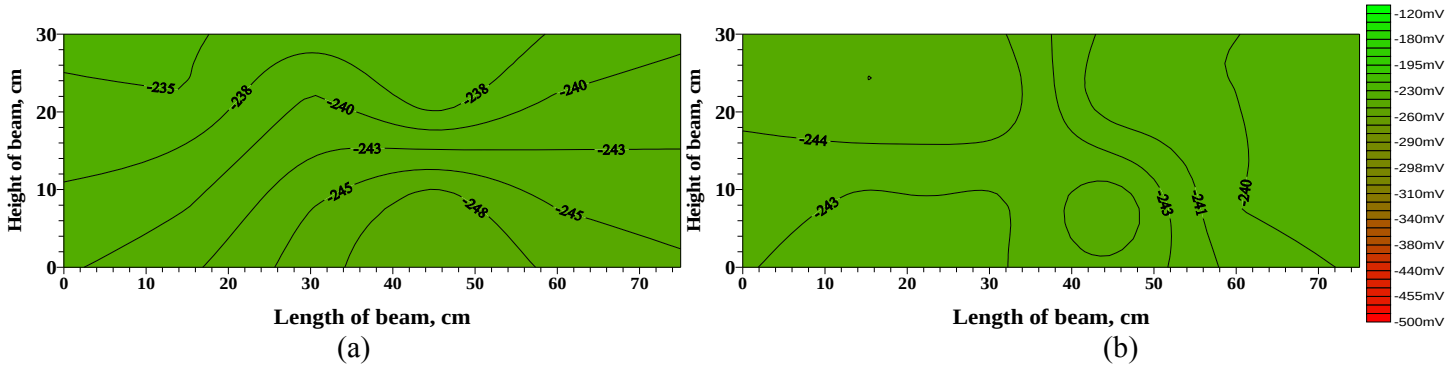


Figure 4.23. Corrosion potential contours in beam specimen TM15-2 exposed in the tidal zone (a) facing inland (b) facing sea.

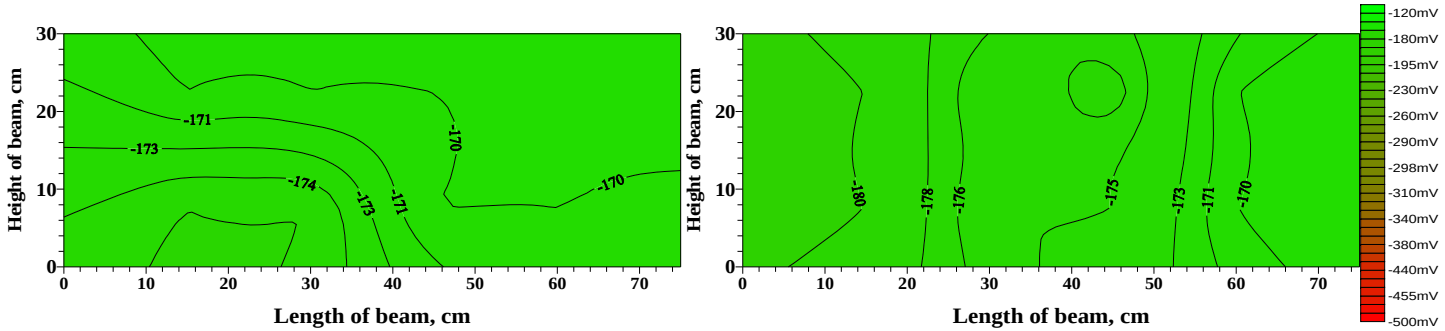


Figure 4.24. Corrosion potential contours in beam specimen TM15-3 exposed in the tidal zone (a) facing inland (b) facing sea.

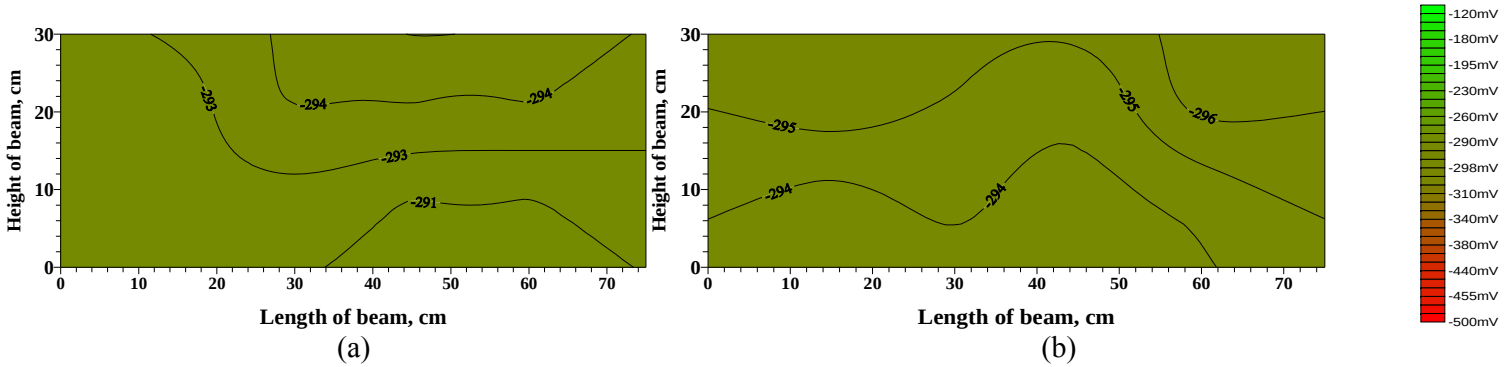
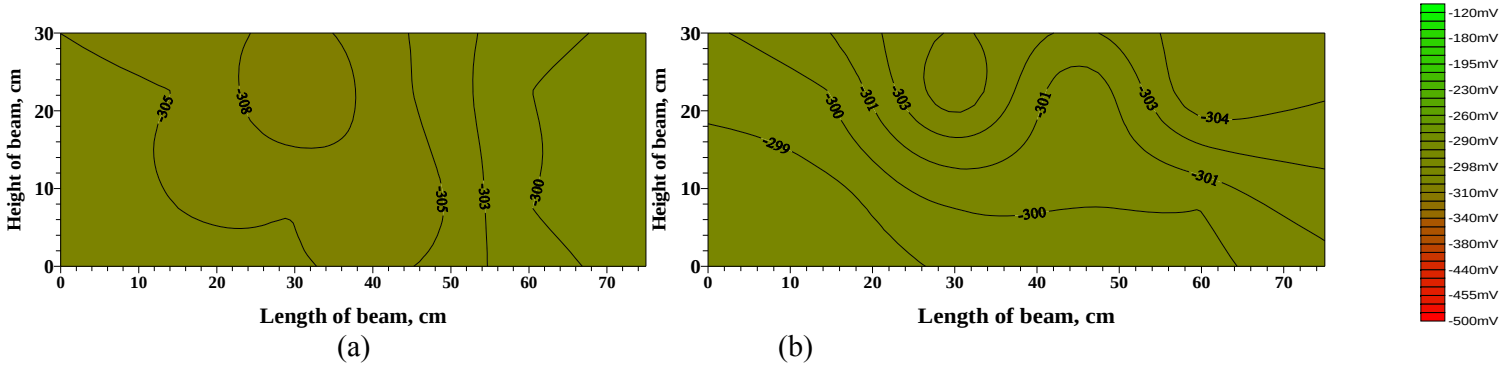
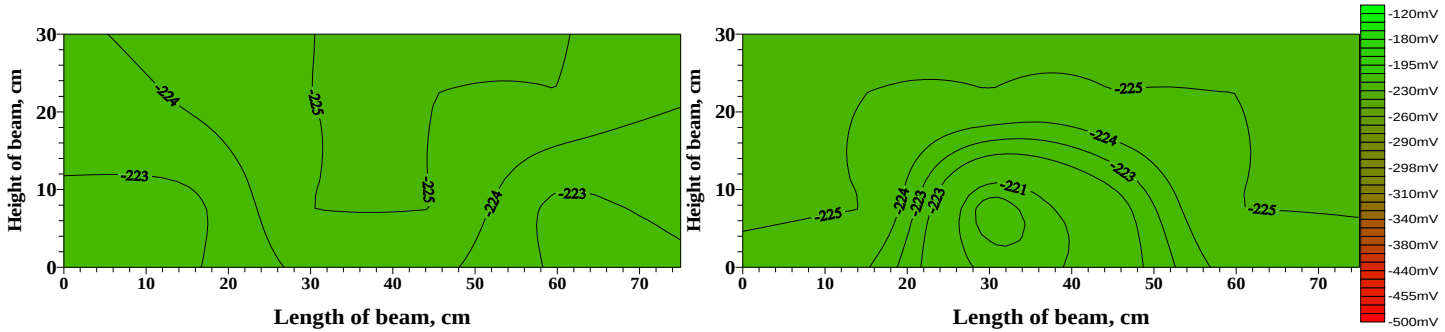


Figure 4.25. Corrosion potential contours in beam specimen TM17-1 exposed in the tidal zone (a) facing inland (b) facing sea.



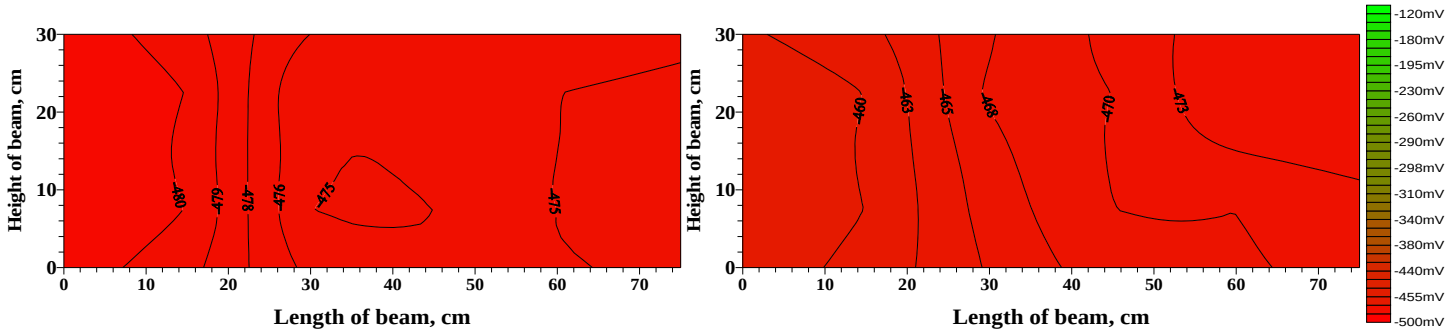
(a) (b)

Figure 4.26. Corrosion potential contours in beam specimen TM17-2 exposed in the tidal zone (a) facing inland (b) facing sea.



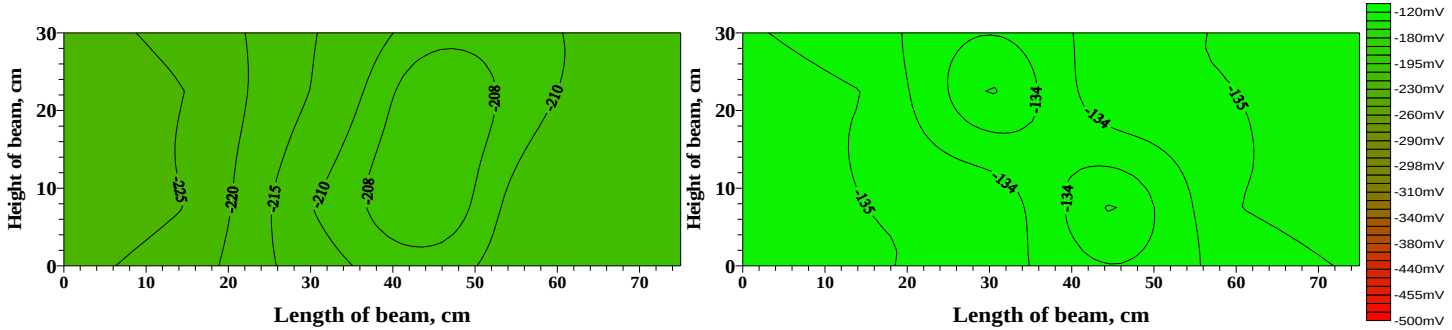
(a) (b)

Figure 4.27. Corrosion potential contours in beam specimen TM17-3 exposed in the tidal zone (a) facing inland (b) facing sea.



(a) (b)

Figure 4.28. Corrosion potential contours in beam specimen TM20-1 exposed in the tidal zone (a) facing inland (b) facing sea.



(a) (b)

Figure 4.29. Corrosion potential contours in beam specimen TM20-2 exposed in the tidal zone (a) facing inland (b) facing sea.

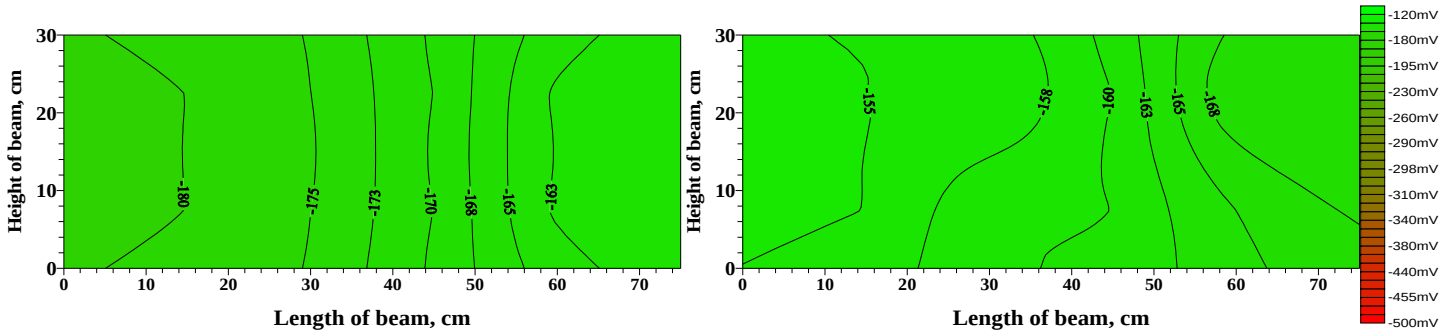


Figure 4.30. Corrosion potential contours in beam specimen TM20-3 exposed in the tidal zone (a) facing inland (b) facing sea.

4.1.3 Chloride Profile

The concentration of chloride required to initiate reinforcement corrosion, known as chloride threshold value, depends on so many factors including the quality of concrete, relative humidity and temperature of concrete, the pH of the pore solution, and the sulfate content. As per ACI 222R, the water soluble chloride limits for new reinforced concrete in wet conditions is 0.08% by weight of cement (about 0.013 % by weight of concrete); ACI 318 specifies 0.15% by weight of cement (about 0.025% by weight of concrete). These values are established for new concrete structures considering that the concrete will absorb additional chloride during service. Other organizations, such as RILEM, specify 0.4% by weight of cement (about 0.06% by weight of concrete).

The chloride concentration in all the concrete specimens prior to field exposure was very low (less than 0.01 %).

The data on chloride diffusion after ten and eight years of field exposure are presented in Table 4.28 and Figure 4.31.

For all the mixes, the chloride concentration is high at the surface (i.e. exterior) and decreases with the depth up to 95 to 100 mm. The average chloride concentration of all the mixes increased with exposure time. After ten years of exposure to the tidal zone, the average chloride concentration by weight of concrete at the surface ranged for TM20 (70% GGBS) which correspond 2.448% by weight of cement. Most of the mixes showed values more than ten times the threshold chloride value of 0.025% by weight of concrete (0.15% by weight of cement) for new concrete specified by ACI 318.

The chloride concentrations at the rebar level (i.e. 75 mm) after ten years of exposure are detailed in Table 4.29 as well as in Figure 4.32. If the threshold is set to a value of 0.025% by weight of concrete (i.e., 0.15% by weight of cement), it can be observed that all the concrete mixes crossed the threshold chloride value indicating the harsh exposure condition. The reported values ranged between 0.04% and 0.1055% by weight of concrete. Mixes TM4 and TM7 (with SF) showed the lowest chloride concentration values compared to the other mixes. The mixes with FA, superpozz and GGBS (TM8, TM15, TM17 and TM20) showed relatively higher values compared to the mixes with SF.

Table 4.28. Chloride concentration after ten years in the specimens placed in the tidal zone.

Mix No.	Chloride ion concentration, % by weight of concrete				
	Depth , mm				
	0-5	10-15	25-30	72-77	95-100
TM1	0.249	0.219	0.129	0.063	0.055
TM2	0.254	0.231	0.162	0.084	0.062
TM3	0.260	0.192	0.139	0.055	0.040
TM4	0.317	0.255	0.130	0.040	0.030
TM7	0.220	0.146	0.100	0.060	0.030
TM8	0.367	0.243	0.146	0.1055	0.023
TM15	0.333	0.258	0.189	0.105	0.055
TM16	0.315	0.240	0.181	0.097	0.056
TM17	0.347	0.281	0.198	0.095	0.056
TM20	0.408	0.221	0.105	0.075	0.047

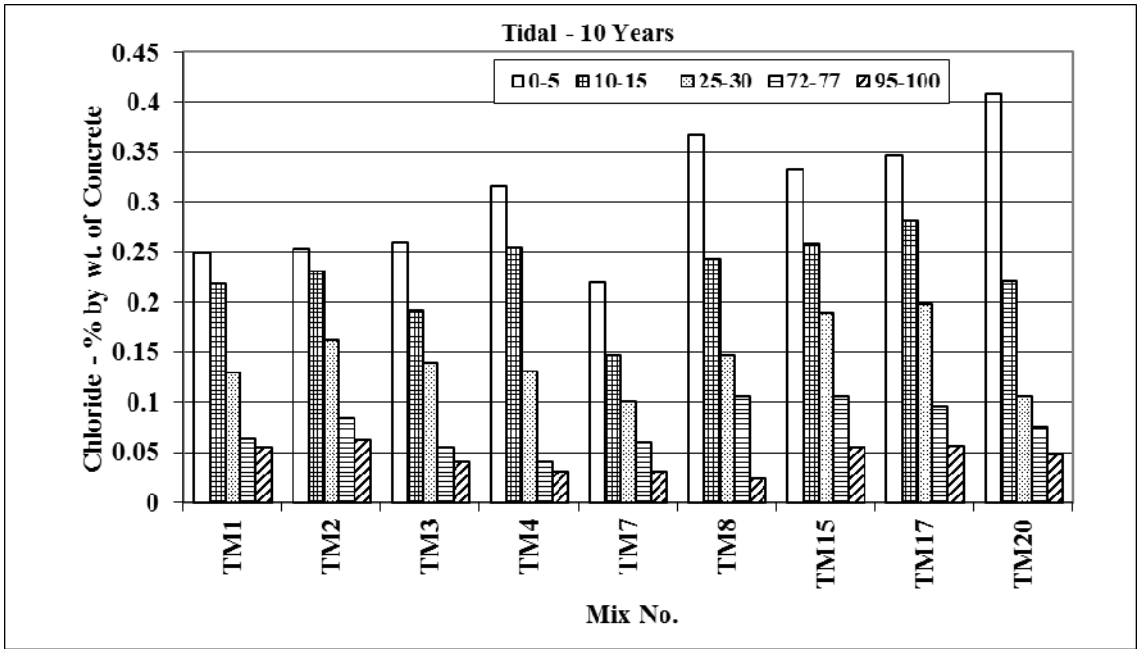


Figure 4.31. Chloride concentration profiles in beams after ten years exposure in the tidal zone.

Table 4.29. Chloride ion concentration at the rebar level.

Mix #	Chloride content, % by weight of concrete
TM1	0.063
TM2	0.084
TM3	0.055
TM4	0.040
TM7	0.060
TM8	0.1055
TM15	0.105
TM17	0.095
TM20	0.075

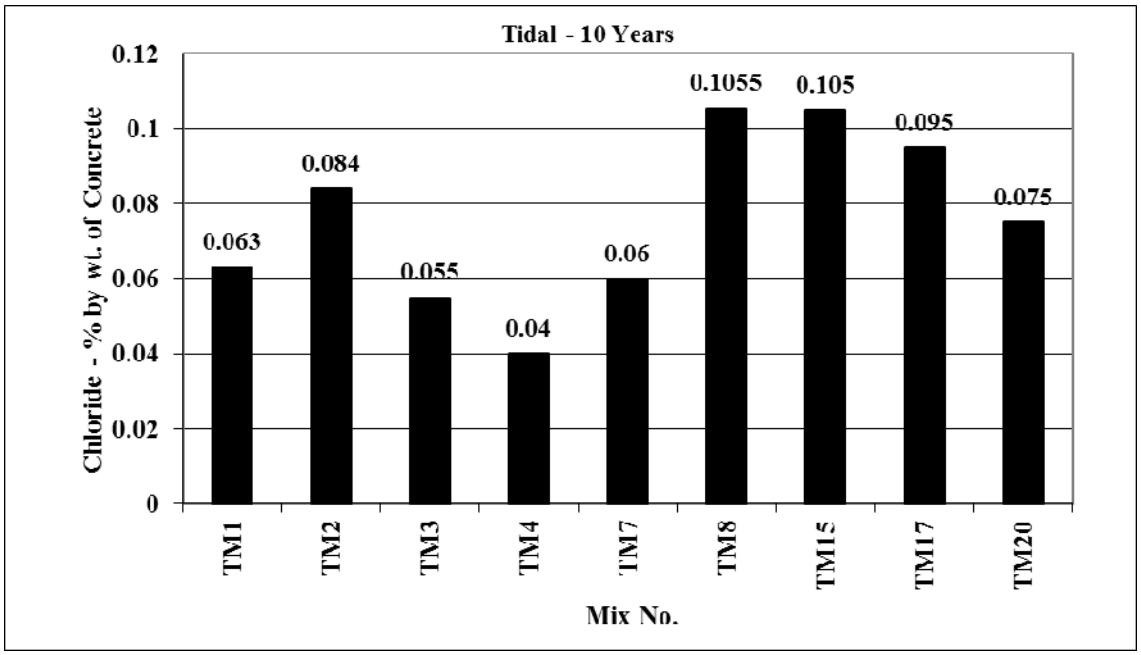


Figure 4.32. Chloride concentration at the rebar level in beams after ten years of exposure in the tidal zone.

4.1.4 Sulfate Profile

The sulfate penetration data indicated that the sulfate concentration increased with exposure period and decreased with the depth of penetration.

The sulfate concentration after ten years is shown in Table 4.30 and Figure 4.33. At the rebar level (depth of 72 to 77 mm), the sulfate concentration ranged between 0.102% and 0.269% by weight of concrete. The sulfate concentration values of more than 0.2% by weight of concrete were noted in mixTM17. The other mixes showed concentrations between 0.1% and 0.2% with

the lowest values noted in the concretes specimens prepared with high cement content, low w/c ratio + SF, 20% FA, and 10 Superpozz (Mixes TM3, TM4, TM8, TM10 and TM15). Mix TM7 (prepared with 8% silica fume) exhibited relatively high sulfate concentration. The obtained results after ten years of exposure did not show strong correlation between using pozzolanic materials and low sulfate concentration.

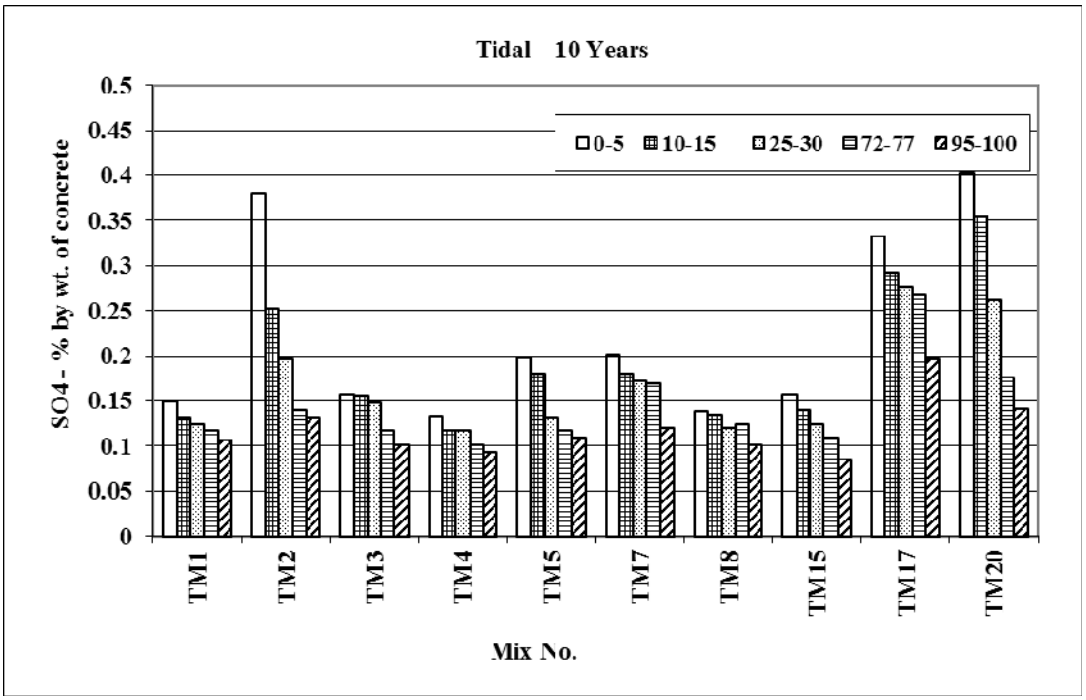


Figure 4.33. Sulfate concentration in beams after ten years of exposure in the tidal zone.

Table 4.30. Sulfate ion profile of the tidal zone beams after ten years exposure.

Mix No.	Sulfate ion concentration, % by wt. of concrete				
	0-5 mm	10-15 mm	25-30 mm	72-77 mm	95-100 mm
TM1	0.149	0.133	0.125	0.117	0.107
TM2	0.381	0.253	0.197	0.141	0.133
TM3	0.157	0.157	0.149	0.117	0.102
TM4	0.133	0.117	0.117	0.102	0.094
TM7	0.201	0.181	0.172	0.170	0.121
TM8	0.138	0.135	0.121	0.125	0.102
TM15	0.157	0.141	0.125	0.110	0.086
TM17	0.333	0.293	0.277	0.269	0.197
TM20	0.404	0.356	0.262	0.177	0.142

4.1.5 pH

Mixes TM17 and TM20 (30% FA and 70% GGBS, respectively) exhibited marginally lower pH values due to the high cement replacement by these two pozzolanic materials. The pH data are given in Table 4.31 and plotted in Figure 4.34. The data indicate that the pH level at all depths, except the surface layer (i.e. 0 to 5 mm), was more than 12.0, which confirms the high alkalinity of bulk concrete for all types of mixtures.

The lower pH values for the surface layer of almost all the concrete mixtures is ascribable the minor carbonation that took place in this exterior layer, which is exposed to atmospheric conditions. The pH values of this layer ranged between 11.38 and 12.20.

Similar to the data reported previously, all the concrete mixes maintained pH values at the rebar level more than 12.0 except for mixes TM17 and TM20 (30% FA and 70% GGBS, respectively) which exhibited marginally lower pH values due to the high cement replacement by these two pozzolanic materials. These data indicated that the high alkalinity of the concrete mixture, which is very important from corrosion perspective, is maintained in all the specimens. The reported pH value of more than 12.0 at the rebar level is still safe from the perspective of corrosion of reinforcing steel.

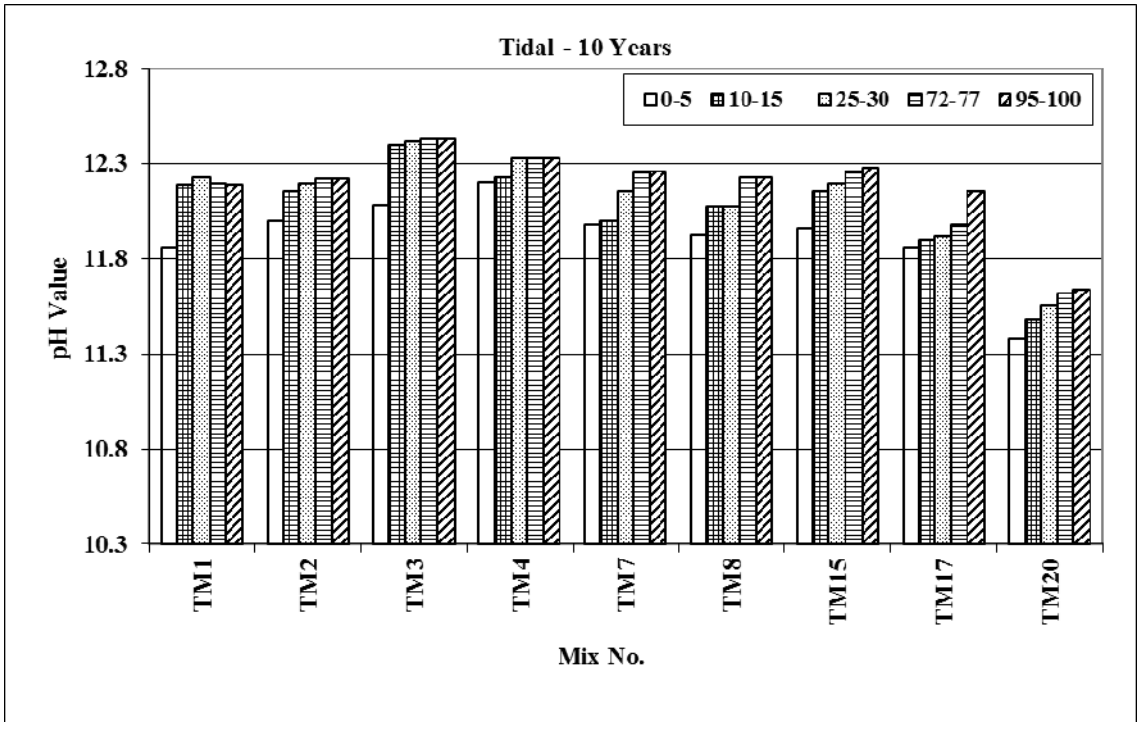


Figure 4.34. pH profiles in beams exposed to the tidal zone.

Table 4.31. pH profile in the tidal zone beams after ten years of exposure.

Mix #	pH					
	Unexposed					
		0-5 mm	10-15 mm	25-30 mm	72-77 mm	95-100 mm
TM1	12.40	11.86	12.19	12.23	12.20	12.19
TM2	12.34	12.00	12.16	12.20	12.22	12.22
TM3	12.42	12.08	12.4	12.42	12.43	12.43
TM4	12.40	12.20	12.23	12.33	12.33	12.33
TM7	12.34	11.98	12.00	12.16	12.26	12.26
TM8	12.41	11.92	12.08	12.08	12.23	12.23
TM15	12.35	11.96	12.16	12.20	12.26	12.28
TM17	12.30	11.86	11.90	11.92	11.98	12.16
TM20	11.98	11.38	11.48	11.56	11.62	11.64

4.1.6 Water Permeability

The water permeability values for all the specimens expose in tidal zone are summarized in Table 4.32, and Fig.4.35. The water permeability of the mixes M1 (control) and M2 (type V cement) showed similar values and comparable to their respective unexposed specimens with about 4.0 cm permeability.

All the pozzolanic concrete mixes have performed well with the average permeability being less than 2.4 cm. However, the best performed mix in this zone were M10, and M15 followed by M7 (8% SF), M8 (20% FA) and M17 (with 30% FA).

Table 4.32. Summary of water permeability values.

Mix #	Water permeability, cm
TM1	4.0
TM2	4.2
TM3	2.7
TM4	2.4
TM7	1.3
TM8	1.3

TM15	0.0
TM17	0.40
TM20	2.80

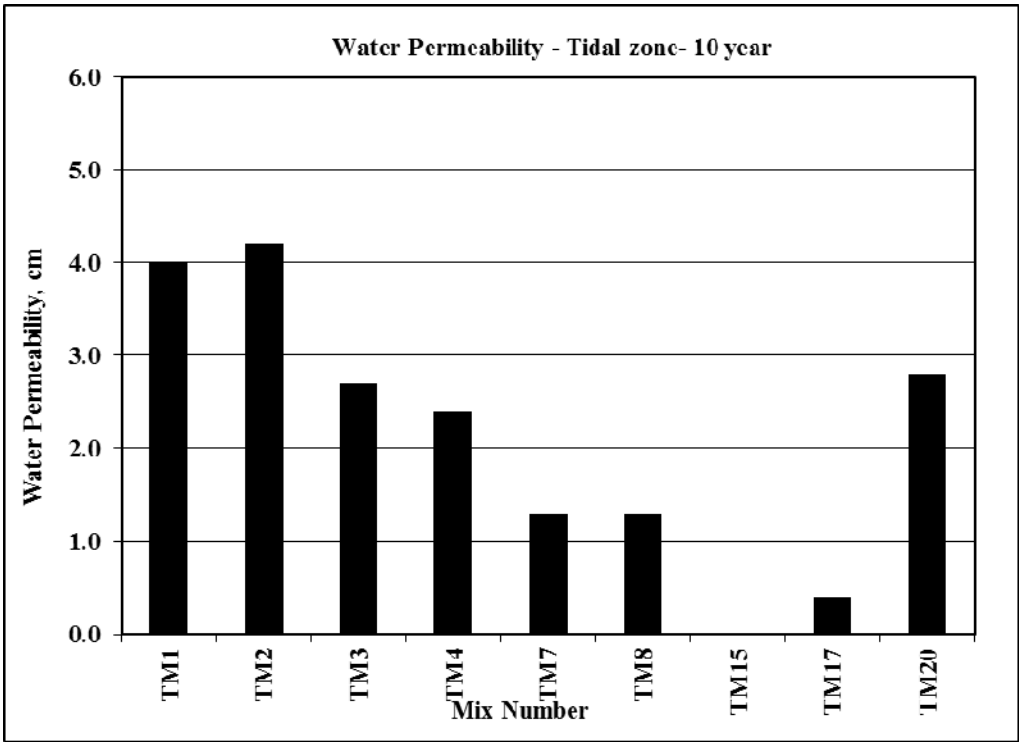


Figure 4.35. Water permeability in tidal zone specimens.

4.1.7 Chloride Permeability

After 10 years of exposure, all the pozzolanic concrete mixes showed very low to low chloride permeability with the exception of mix M20 (with 70% GGBS), as shown in Table 4.33 and depicted in Figure 4.36. The best performance was observed by concrete mixes M8 (20% FA), M15 (10% Superpozz) and M17 (30% FA) with values less than 500 coulombs at a very low range. Moreover, the chloride permeability of mixes M2 (Type V cement), and M20 (70 % GGBFS) increased or continued in the high range with values more than 4000 coulombs. While the chloride permeability of mix M3 (high cement content) showed moderate range with 3357 coulombs. The chloride permeability of mix M7 (8% SF) and the control mix M1 after ten years of exposure exhibited low range.

Table 4.33. Chloride permeability in the tidal zone specimens.

Mix #	Chloride permeability, Coulombs	
TM1	Unexposed	After 10 years
TM1	1541.3	1201.7
TM2	3821.9	5865.0
TM3	1616.0	3357.0
TM4	535.7	3476.3
TM7	336.5	1369.7
TM8	1024.0	363.7
TM15	1447.2	274.7
TM17	518.3	496.0
TM20	474.3	502.3

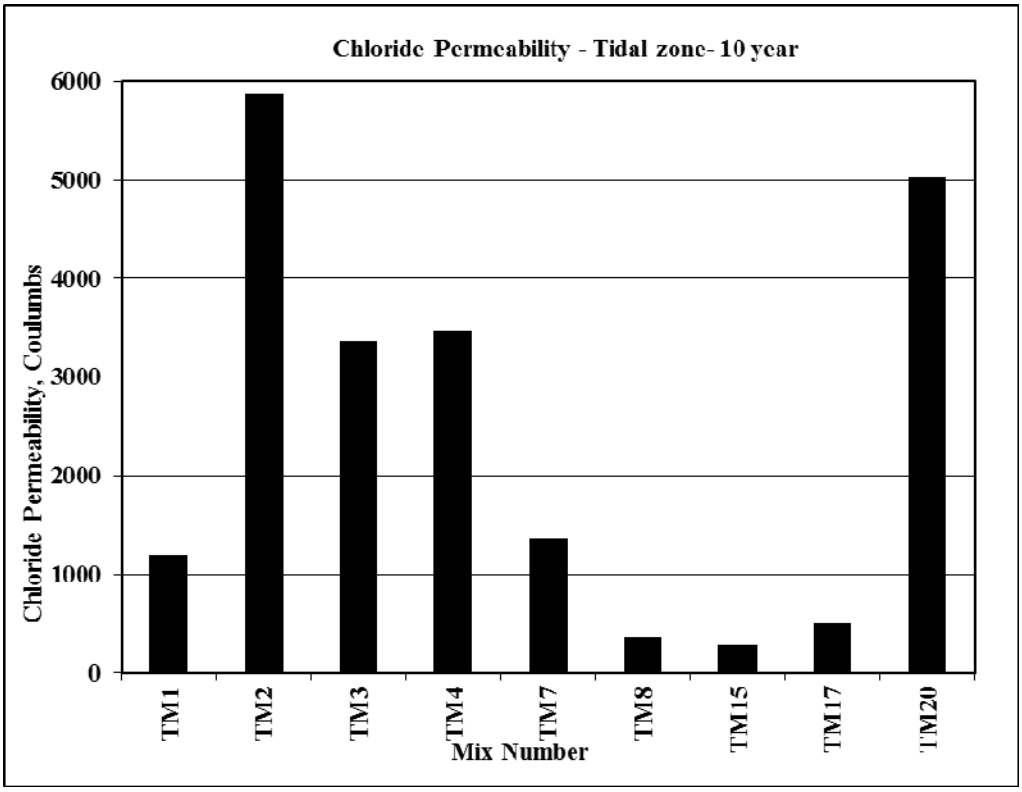


Figure 4.36. Chloride permeability in tidal zone specimens.

4.1.8 Electrical Resistivity

The tidal zone is the most aggressive zone with respect to corrosion of reinforcing steel. In this zone, the specimens are subjected to cycles of high and low tides, hence high and low moisture content of concrete.

The electrical resistivity values of the specimens exposed in the tidal zone are presented in Figures 4.37 and 4.38 at the initial (as retrieved) and 3% moisture content, respectively. The electrical resistivity values at the initial and at 3% moisture content is detailed in Table 4.34 and 4.35.

The initial electrical resistivity values of all mixes do not follow consistent trend. For some mixes the values of the electrical resistivity did not change significantly with exposure time and for most of them noticeable reduction is observed. For most of the mixes, this can be attributed to the initial moisture content of the retrieved specimens.

After ten years exposure in the tidal zone the electrical resistivity for all mixes ranged from 31.18 to 113.10 kOhm.cm with the corresponding moisture content values of 2.45 and 2.76%, respectively. Mix M20 (70% GGBFS) continued to show the best performance in this zone with negligible risk of corrosion. The pozzolanic mixes showed the best performance with values above 50 K-Ohm-cm with negligible risk of corrosion. Mix M1 (Type I cement) was better than mix M2 (Type V cement) and both with moderate risk of corrosion.

At 3% moisture content, the electrical resistivity values (Figure 4.6.4) after ten years of exposure ranged from 18.99 kOhm.cm being the lowest to 199.24 kOhm.cm the highest resistivity. However, after ten years of exposure, the electrical resistivity with most of the mixes are within the range of 10 to 50 kOhm.cm with moderate risk of corrosion. While the values for the pozzolanic mixes M7 (8% SF) and M8 (20% FA) showed 71.23 and 50.04 kOhm.cm, respectively with low risk of corrosion. Similar to the results of initial moisture content, mix M20 showed superior performance at 199.24 kOhm.cm with negligible risk of corrosion.

In general, the tidal zone has the most adverse effect on the electrical resistivity of all concrete mixes which can be attributed to the chloride and salt contamination from seawater.

Table 4.34. Electrical resistivity of concrete specimens at retrieval moisture content.

Mix #	Tidal Zone	
	Moisture content, %	**Electrical Resistivity, kOhm-cm**
TM1	2.43	42.09
TM2	2.31	34.45
TM3	2.64	38.61
TM4	2.80	40.14
TM7	2.82	78.60
TM8	2.26	110.21
TM15	2.36	63.14
TM17	2.31	55.85
TM20	2.76	113.10

Table 4.35. Electrical Resistivity of concrete specimens at three percent moisture content.

Mix #	Tidal Zone	
	Moisture content, %	**Electrical Resistivity, kOhm.cm**
TM1	3.00	24.67
TM2	3.00	20.57
TM3	3.00	25.55
TM4	3.00	44.28
TM7	3.00	71.23
TM8	3.00	50.04
TM15	3.00	38.94
TM17	3.00	30.85
TM20	3.00	199.24

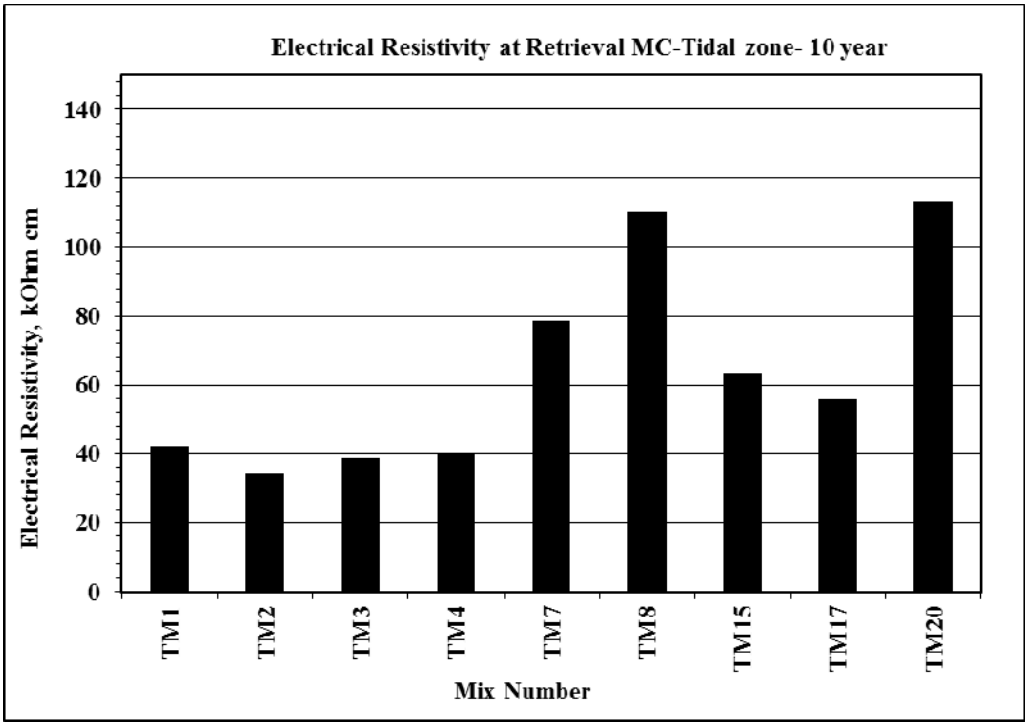


Fig 4.37. Electrical Resistivity of concrete specimens at retrieval moisture content.

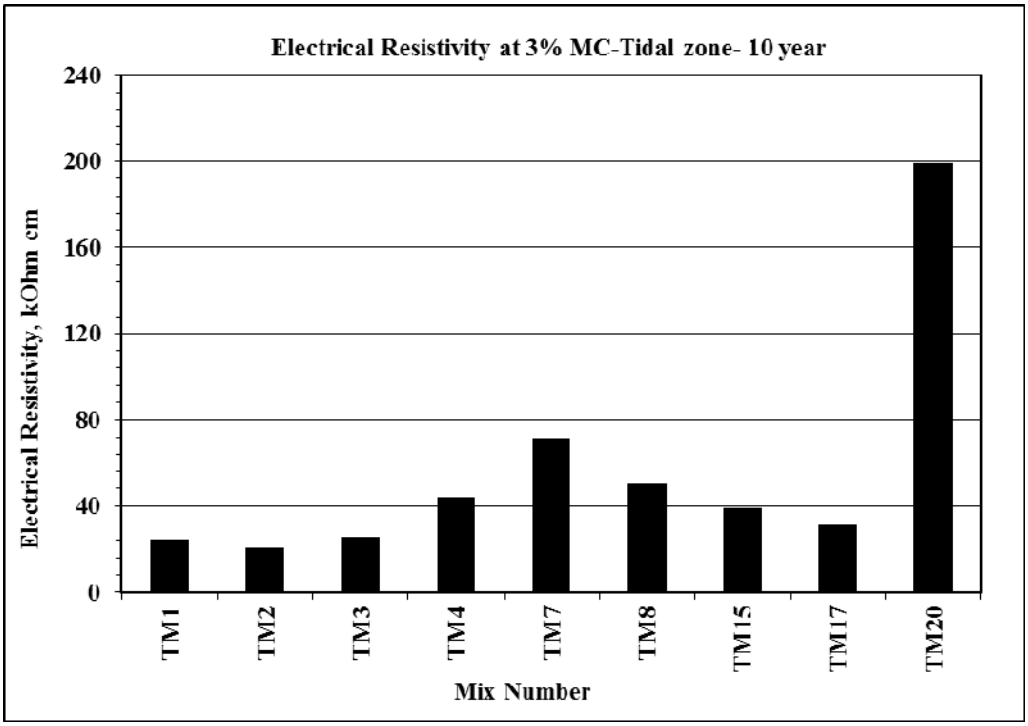


Figure 4.38. Electrical Resistivity of concrete specimens at three percent moisture content.

4.1.9. Water Absorption

The water absorption values for the specimens in tidal zone are summarized in Table 4.36 and depicted in Figure 4.39. The water absorption values of all the mixes are less than their respective values of the unexposed specimen. The water absorption in of mixesTM1 (Type I cement) and TM2 (Type V cement) was relatively less than the corresponding unexposed specimens.

Among the pozzolanic concrete, the water absorption was low in mixes TM8 (20% FA), TM15 (10% superpozz), TM17 (30% FA) and TM20 (70% GGBFS).

In general, the water absorption values of all the mixes exposed for 10 years in the tidal zone ranged from 3.53 to 4.60% and all the values are less than their respective values of the unexposed specimens.

Table 4.36. Water Absorption in concrete specimens exposed to the tidal zone.

Mix #	Absorption, %
TM1	3.63
TM2	4.12
TM3	4.00
TM4	3.95
TM7	4.08
TM8	3.63
TM15	3.65
TM17	3.57
TM20	3.53

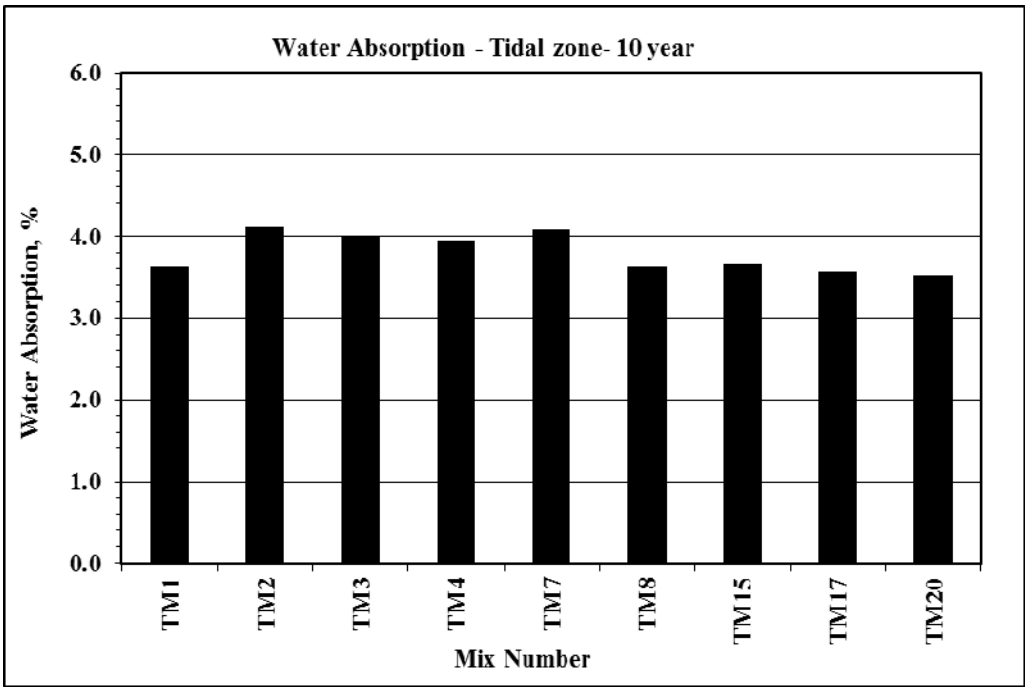


Figure 4.39. Water absorption in concrete specimens exposed in the tidal zone.

4.1.10 Compressive Strength

The average values of compressive strength of specimens exposed in the tidal zone are summarized in Table 4.37 and depicted in Figure 4.40. There is no clear trend regarding the compressive strength. An increase in compressive strength was noted in some mixes while reverse was the case in others.

Maximum compressive strength was noted in Mix TM1 with Type I cement, the compressive strength being around 62.43 MPa. This mix was significantly superior to mix TM2 (Type V cement). In general, the addition of the pozzolanic admixtures (8% SF, 20% FA, 30% FA, 10% Super Pozzlan 70% GGBS) continued to show comparatively high compressive strength values; however these values were less than those exhibited by mix TM1.

Table 4.37. Compressive strength of specimens placed in the tidal zone.

Mix #	Compressive Strength, MPa
TM1	58.16
TM2	47.24
TM3	47.83
TM4	54.12
TM7	56.54
TM8	51.44
TM15	57.15
TM17	52.07
TM20	53.72

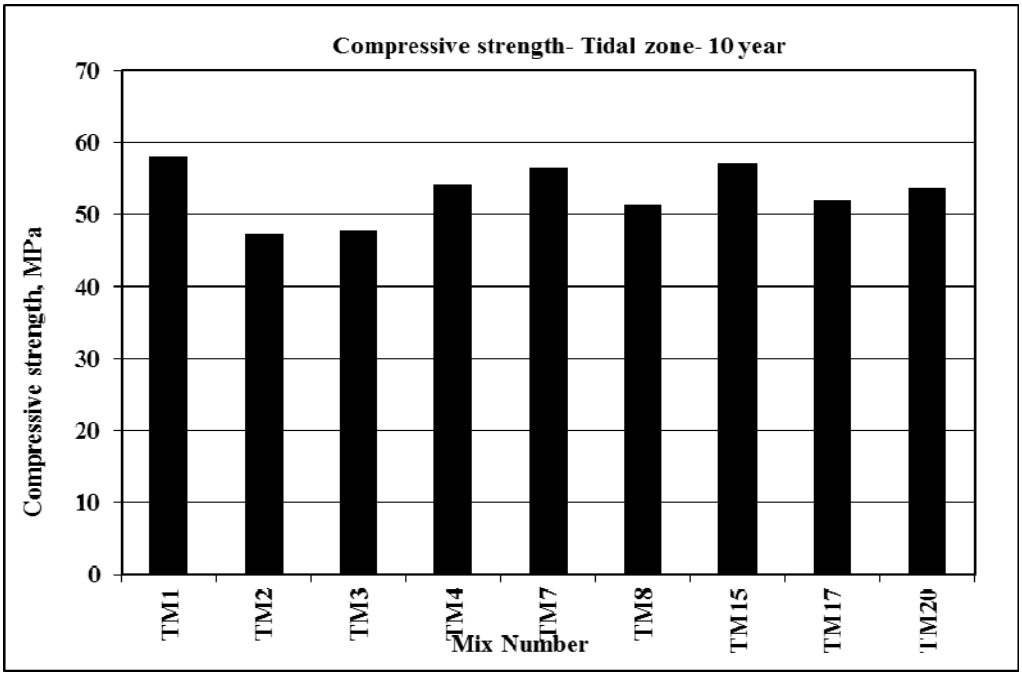


Figure 4.40. Compressive strength of specimens placed in the tidal zone.

4.1.11. Depth of Carbonation

The depth of carbonation in the specimens placed in the tidal zone are summarized in Table 4.38. Carbonation was not detected in any one of the specimens, except in those prepared with 30% fly ash (TM17). However, the depth of carbonation was only 1.5 mm.

Table 4.38. Depth of carbonation in the specimens placed in the tidal zone.

Mix #	Depth of carbonation, mm
TM1	0
TM2	0
TM3	0
TM4	0
TM7	0
TM8	0
TM15	0
TM17	1.5
TM20	0

4.1.12. Morphology

Figures. 4.41 shows the SEM micrograph and EDS spectra for specimen TM1 (Type I cement concrete) exposed to tidal zone. TheEDS spectra show the presence of calcium, silica, oxygen, iron, sulfur, sodium and aluminum. The sulfur and aluminum contents were 1.02% and 1.29% respectively. The presence of sulfur and aluminum indicates the formation of ettringite. This can be noted in the SEM as well.

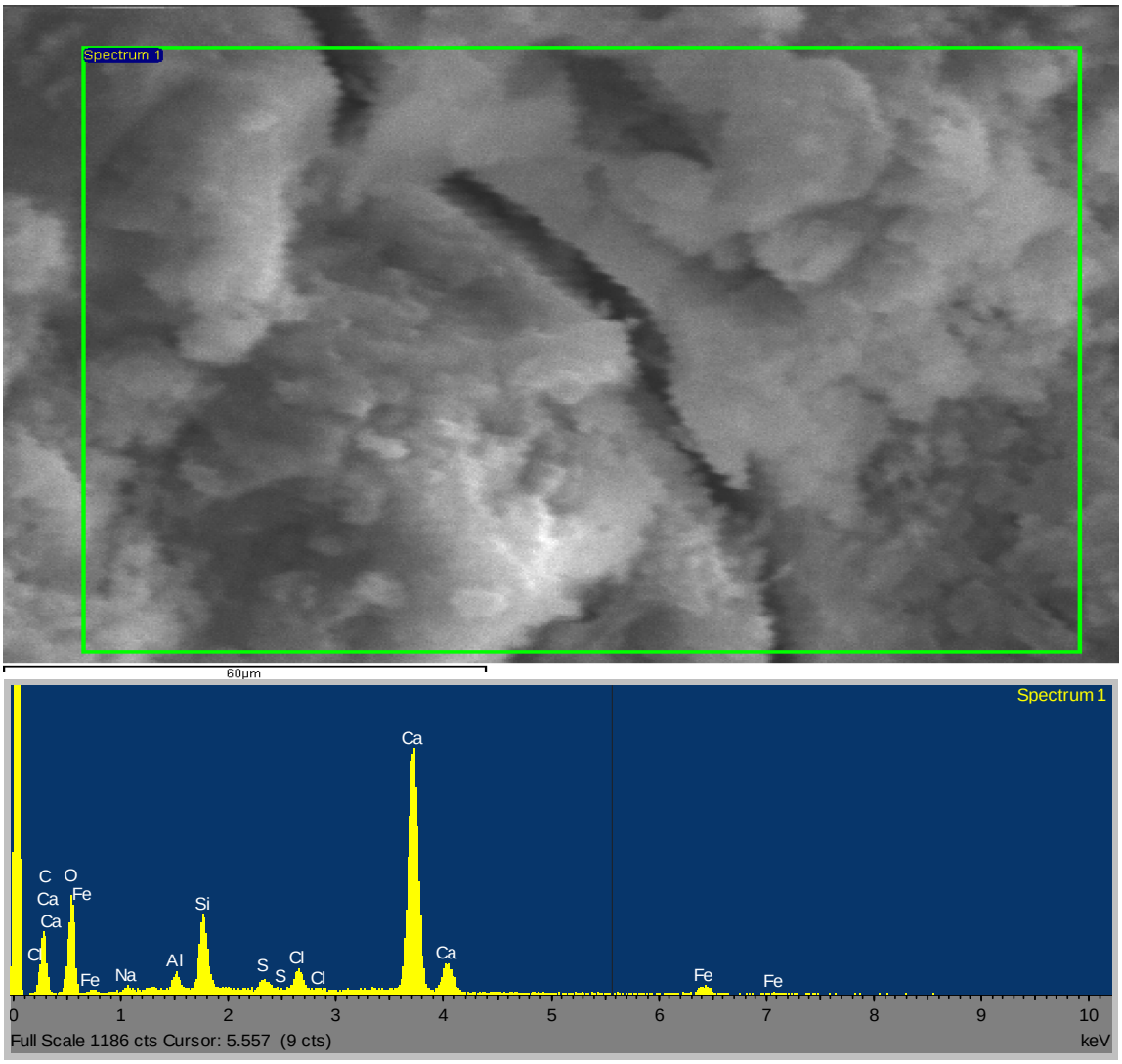
Figures 4.42 and 4.43 show the SEM micrograph and EDS spectra for mix TM2 (Type V cement concrete) exposed to tidal zone. The EDS spectra shows the presence of calcium, silica, oxygen, iron, sulfur, sodium and aluminum. The spectra 2 in Figure 4.42, which is the close-up of a selected area, show 2.91% sulfur and 1.79% aluminum, indicating the presence of ettringite. The SEM in Figure 4.43 shows the presence of ettringite. The EDS spectra shows 2.09% sulfur and 5.03% aluminum, indicating the presence of ettringite. The above results show that sulfate attack occurred in Type V cement concrete exposed to tidal zone due to formation of ettringite.

Figures 4.44 through 4.46 show the SEM micrographs and EDS spectra for mixtures TM7 (Type I cement concrete containing 8% silica fume) exposed to tidal zone. The EDS spectra shows the presence of calcium, silica, oxygen, sodium, potassium, magnesium and aluminum. It should be noted that sulfur was not present in thisspecimen indicating the absence of sulfate attack.

Figures 4.47 through 4.50 show the SEM micrographs and EDS spectra for mix TM17 (Type I cement concrete containing 30% fly ash) exposed to tidal zone. The spectra shows the presence of calcium, silica, oxygen, sodium, potassium, magnesium and aluminum. Figure 4.48 shows 1.11% sulfur and 2.49% aluminum while sulfur was absent in other spectra. The presence of sulfur and aluminum indicates the presence of ettringite and hence the chances of sulfate attack in this specimen.

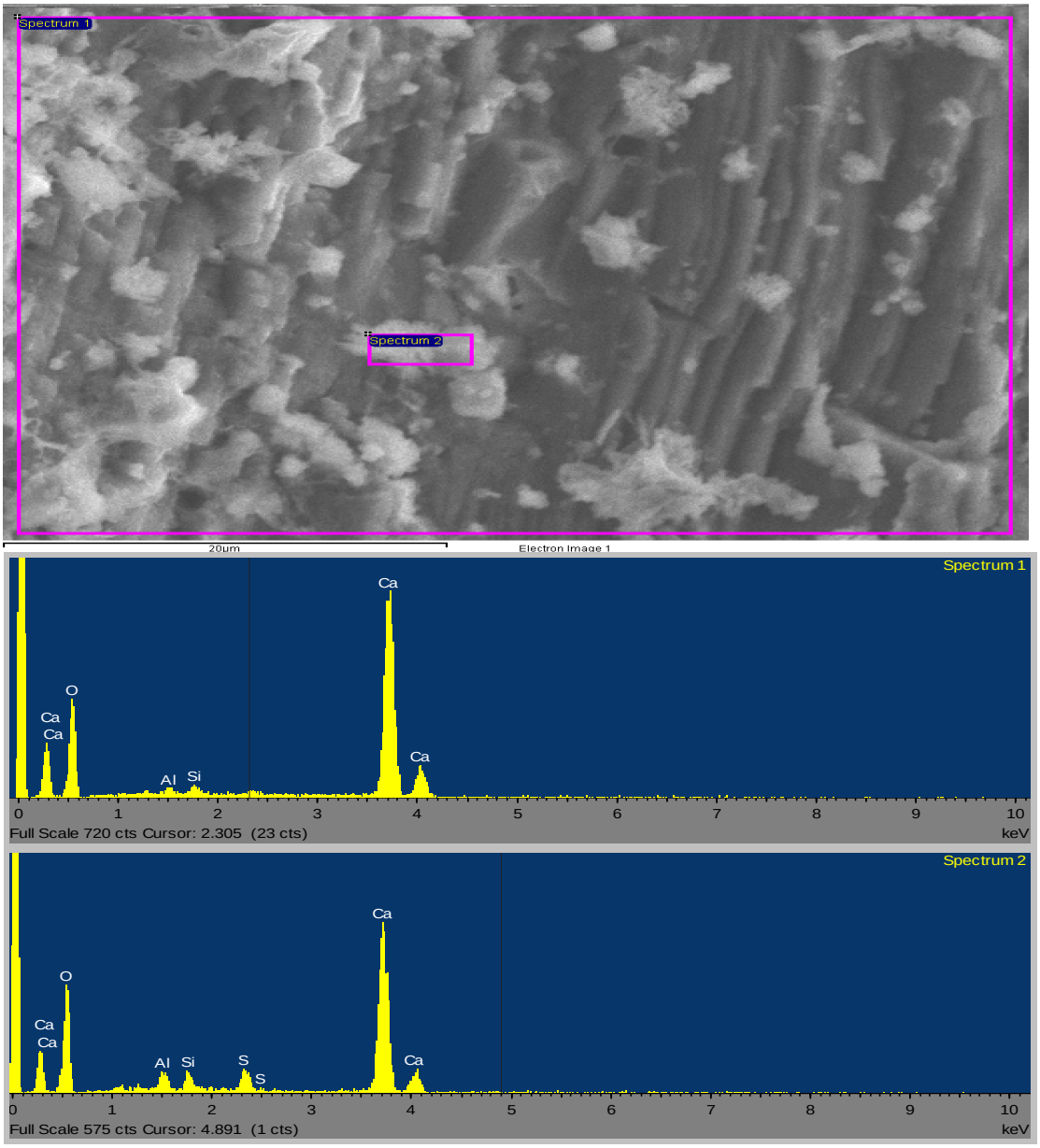
Figures 4.51through 4.53 show the SEM micrographs and EDS spectra for mix TM20 (Type I cement concrete containing 70% blast furnace slag) exposed to tidal zone. The spectra shows the presence of calcium, silica, oxygen, sodium, potassium, magnesium and aluminum. The absence of sulfur indicates that there was no sulfate attack in this specimen.

The results of the SEM micrographs and EDS spectra of concrete specimens exposed to the tidal zone are summarized in Table 4.59. The results show that Type I cement concrete containing silica fume and blast furnace slag did not suffer sulfate attack in the tidal zone. Therefore, these cements are recommended for tidal zone.



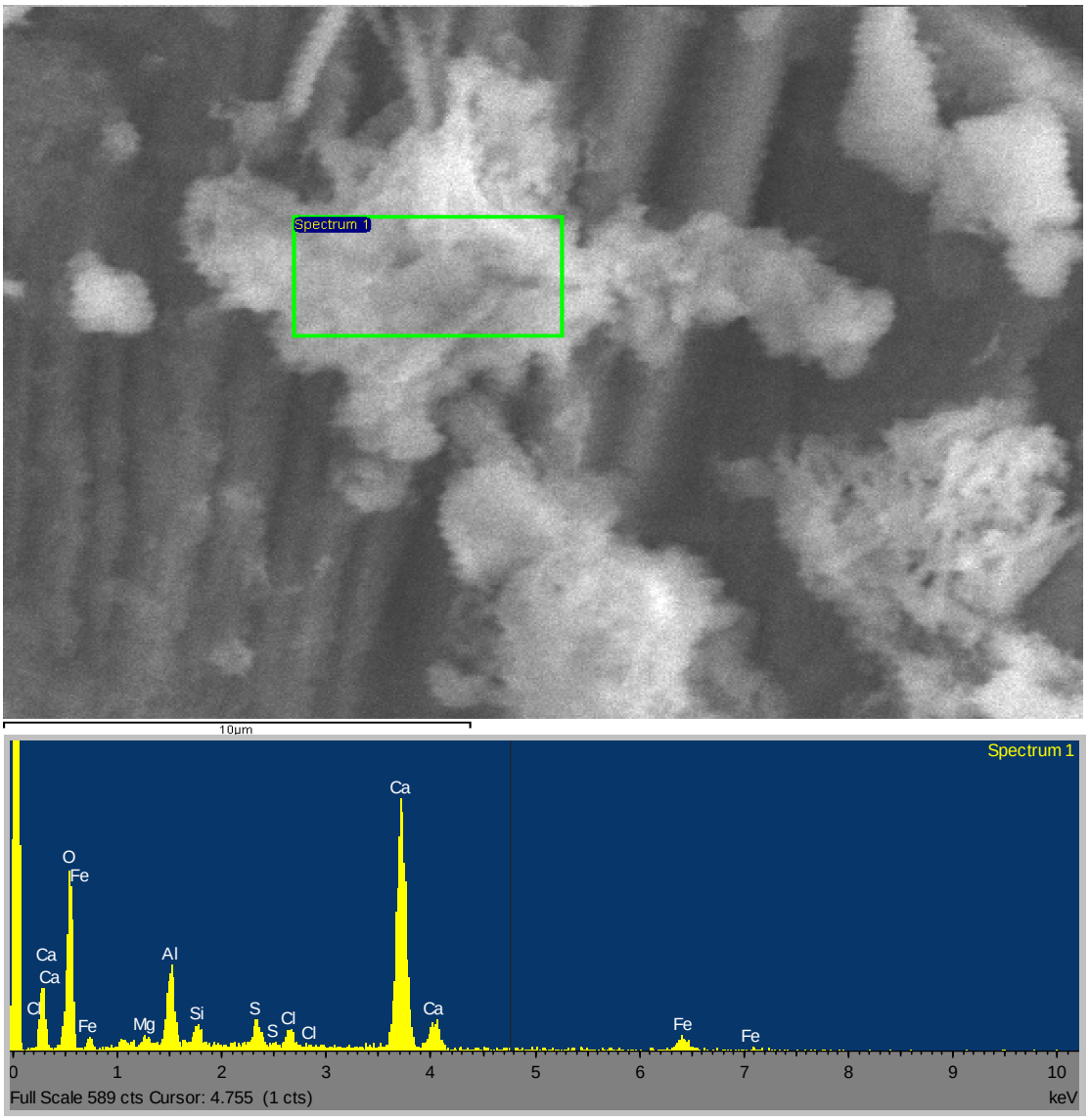
Element	O	Na	Al	Si	S	Cl	Ca	Fe	Total
Weight, %	42.13	0.53	1.29	5.96	1.02	2.58	41.94	4.56	100.00

Figure 4.41. SEM Micrograph and EDS of mix TM1.



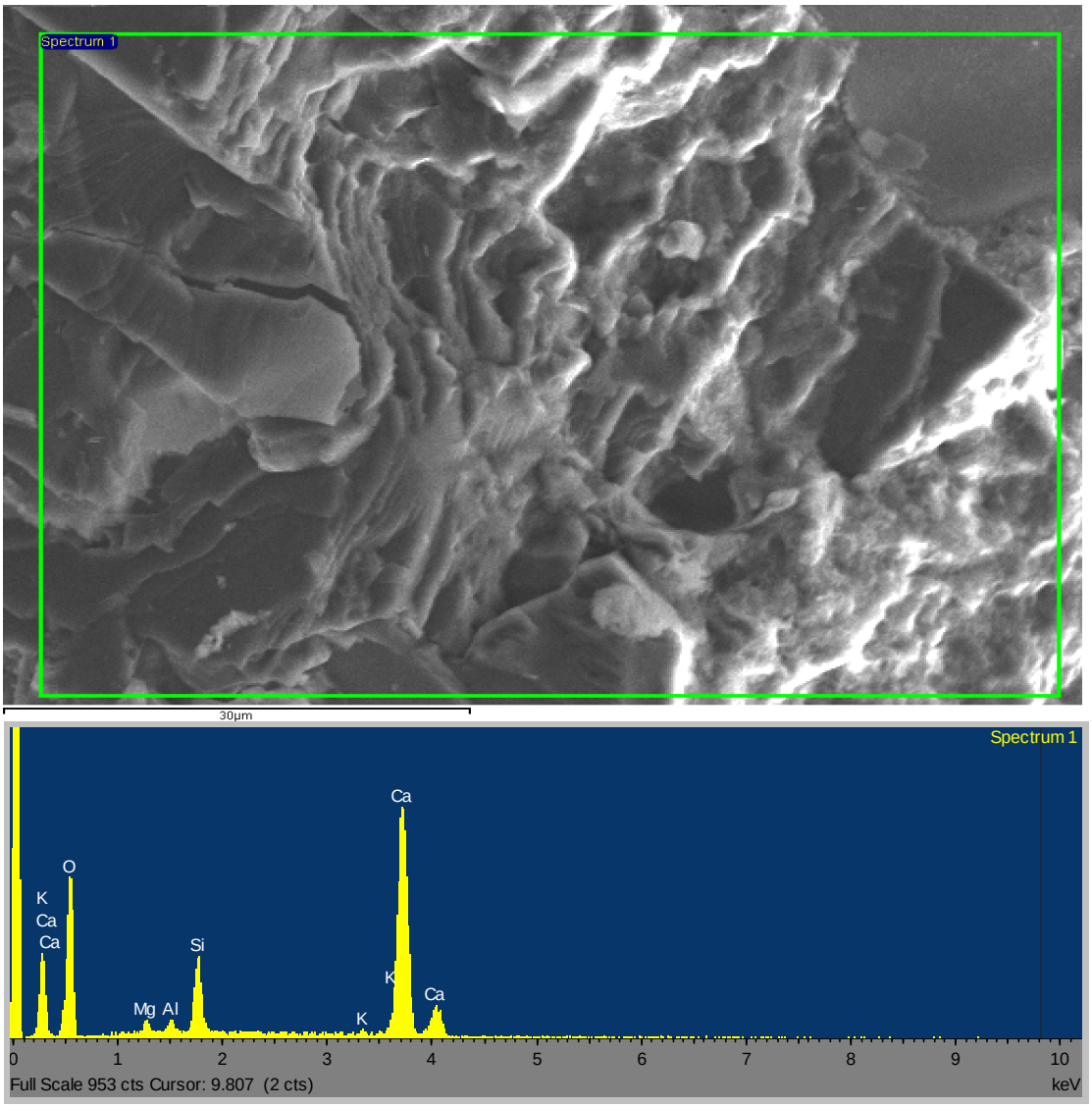
Element	O	Al	Si	S	Ca	Total
Spectrum 1, weight %	53.41	0.61	0.78		45.21	100.00
Spectrum 2, weight %	54.19	1.79	1.94	2.91	39.16	100.00

Figure 4.42. SEM Micrograph and EDS Spectra of mix TM2.



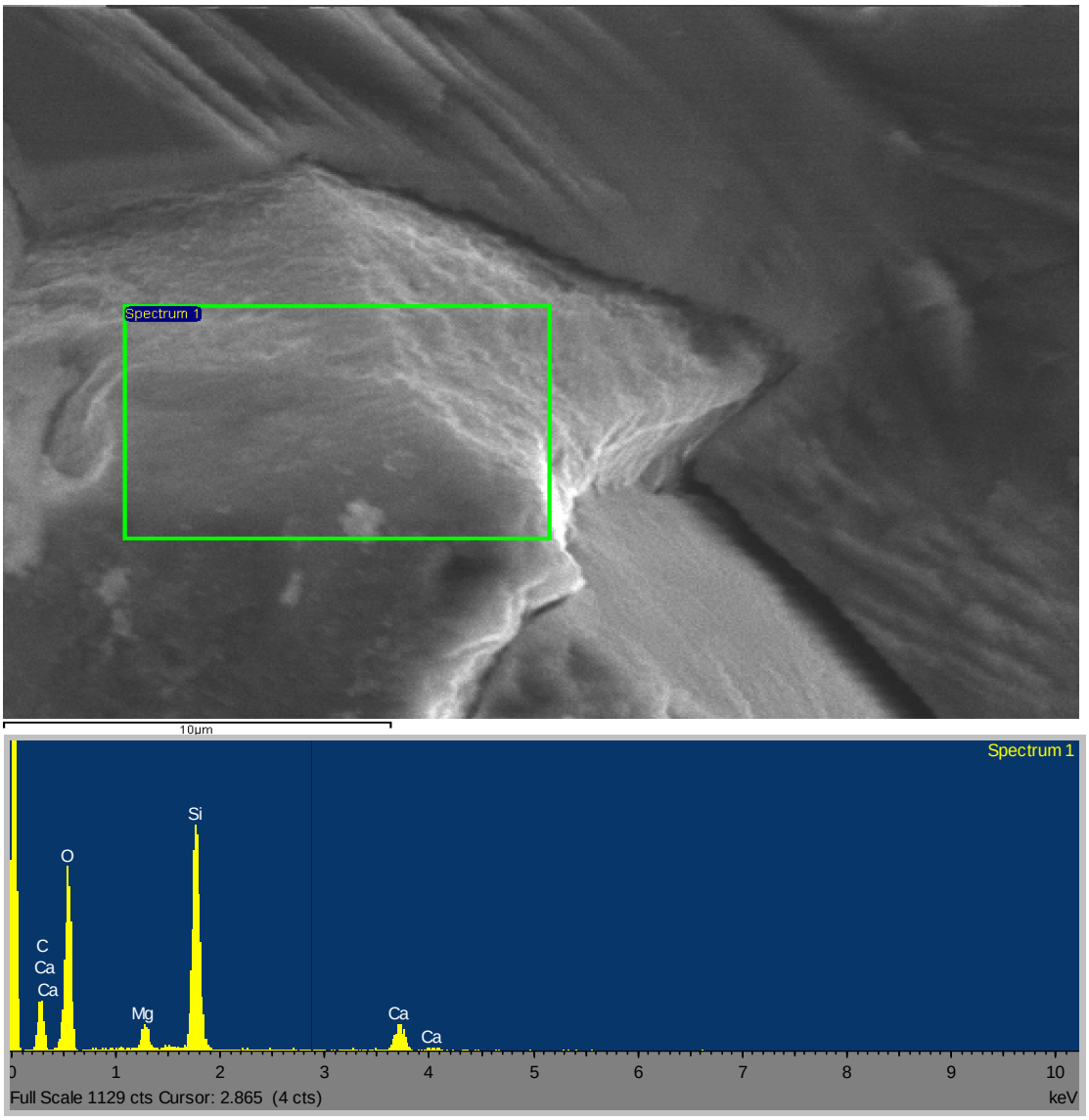
Element	O	Mg	Al	Si	S	Cl	Ca	Fe	Total
Weight, %	49.90	0.65	5.03	1.30	2.09	1.73	32.92	6.38	100.00

Figure 4.43. SEM Micrograph and EDS Spectra of mix TM2.



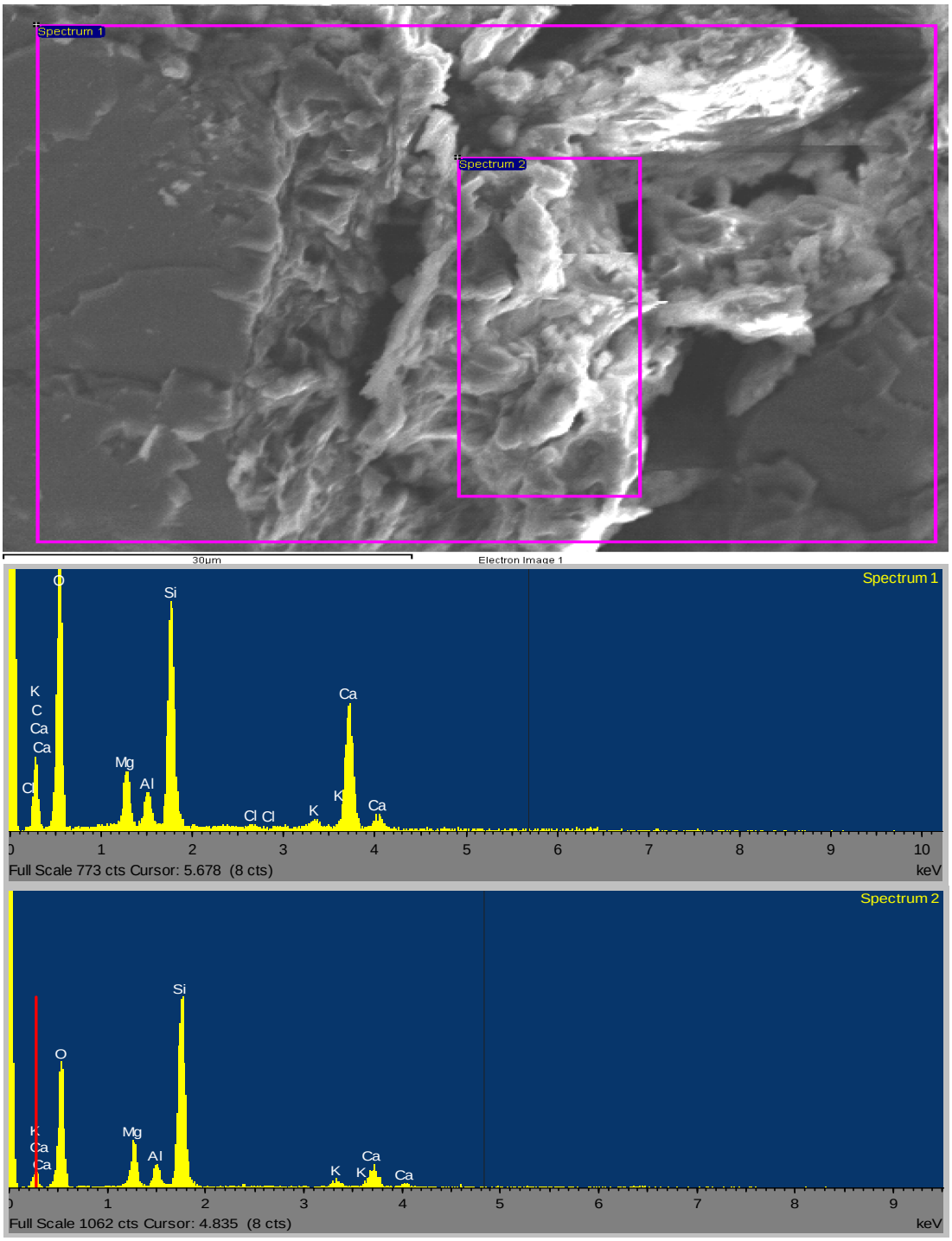
Element	O	Mg	Al	Si	K	Ca	Total
Weight, %	55.17	0.93	0.88	5.57	0.47	36.98	100.00

Figure 4.44. SEM Micrograph and EDS spectra of mix TM7.



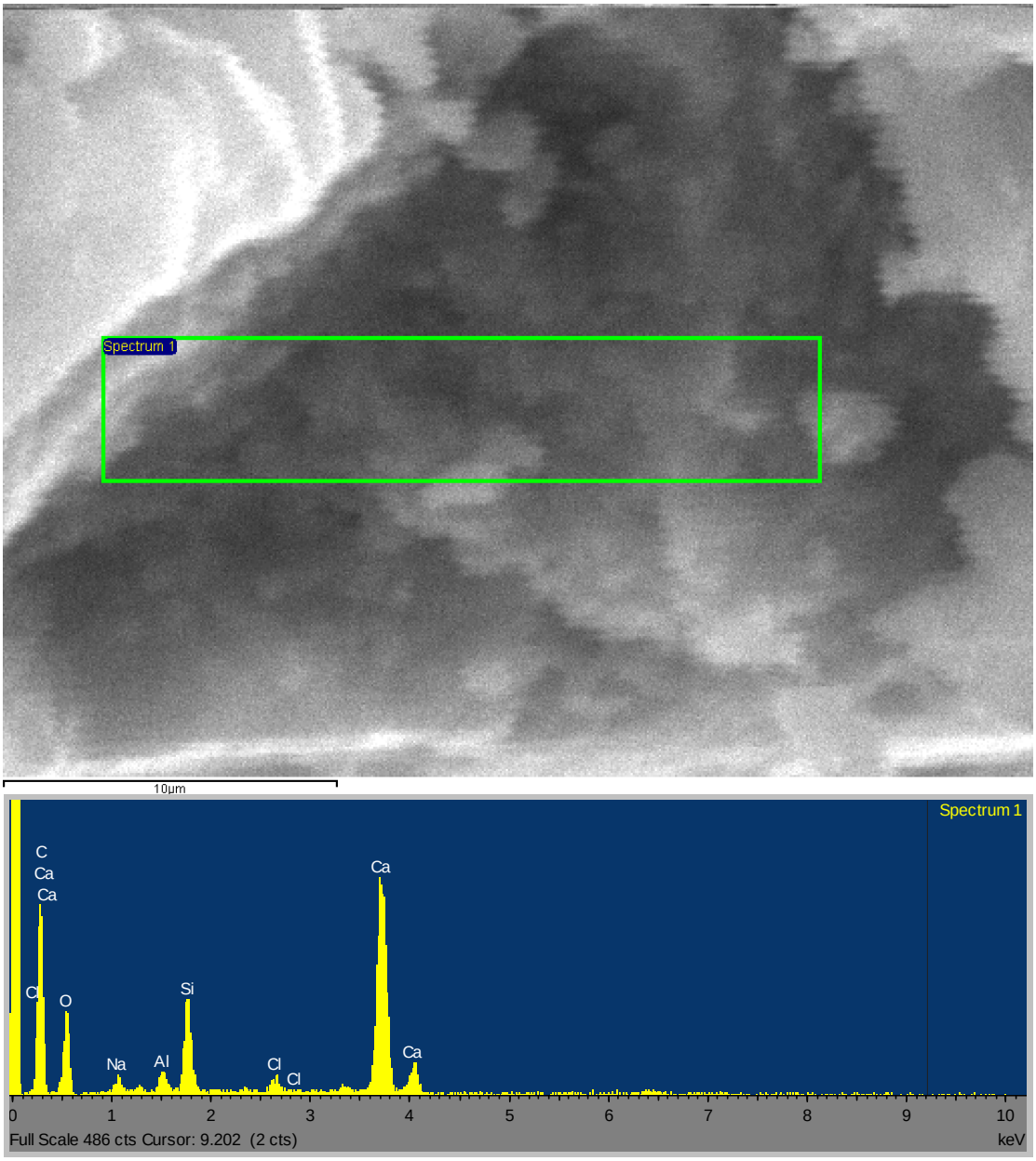
Element	O	Mg	Si	Ca	Total
Weight %	59.56	3.23	29.27	7.94	100.00

Figure 4.45. SEM Micrograph and EDS Spectra of mix TM7.



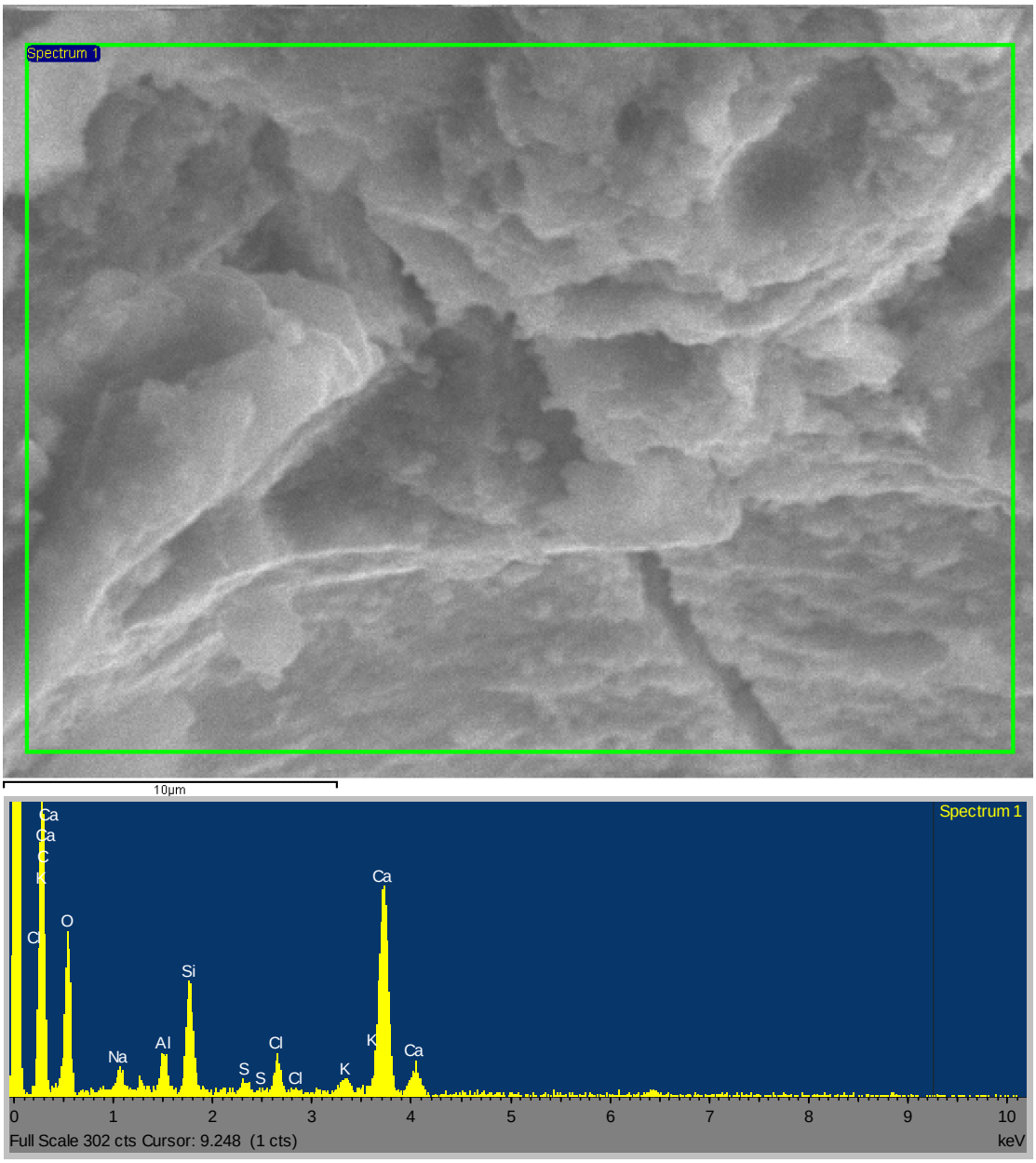
Element	O	Mg	Al	Si	Cl	K	Ca	Total
Spectrum 1 (wt. %)	58.63	3.91	2.09	15.74	0.31	0.84	18.47	100.00
Spectrum 2 (Wt. %)	52.05	6.48	3.01	29.85		1.74	6.87	100.00

Figure 4.46. SEM Micrograph and EDS spectra of mix TM7.



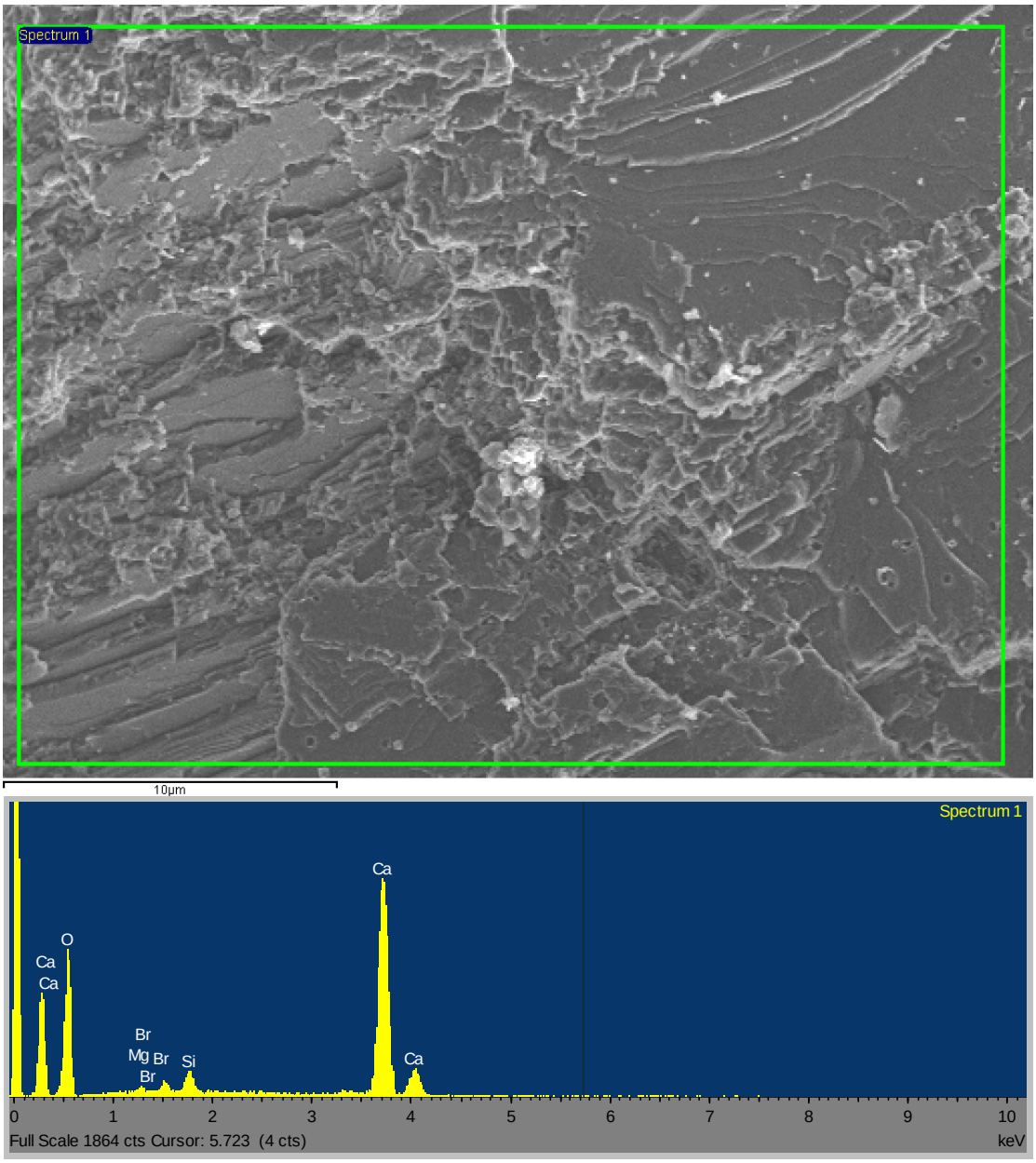
Element	O	Na	Al	Si	Cl	Ca	Total
Weight, %	42.59	1.57	1.75	8.56	1.97	43.56	100.00

Figure 4.47. SEM Micrograph and EDS Spectra of mix TM17.



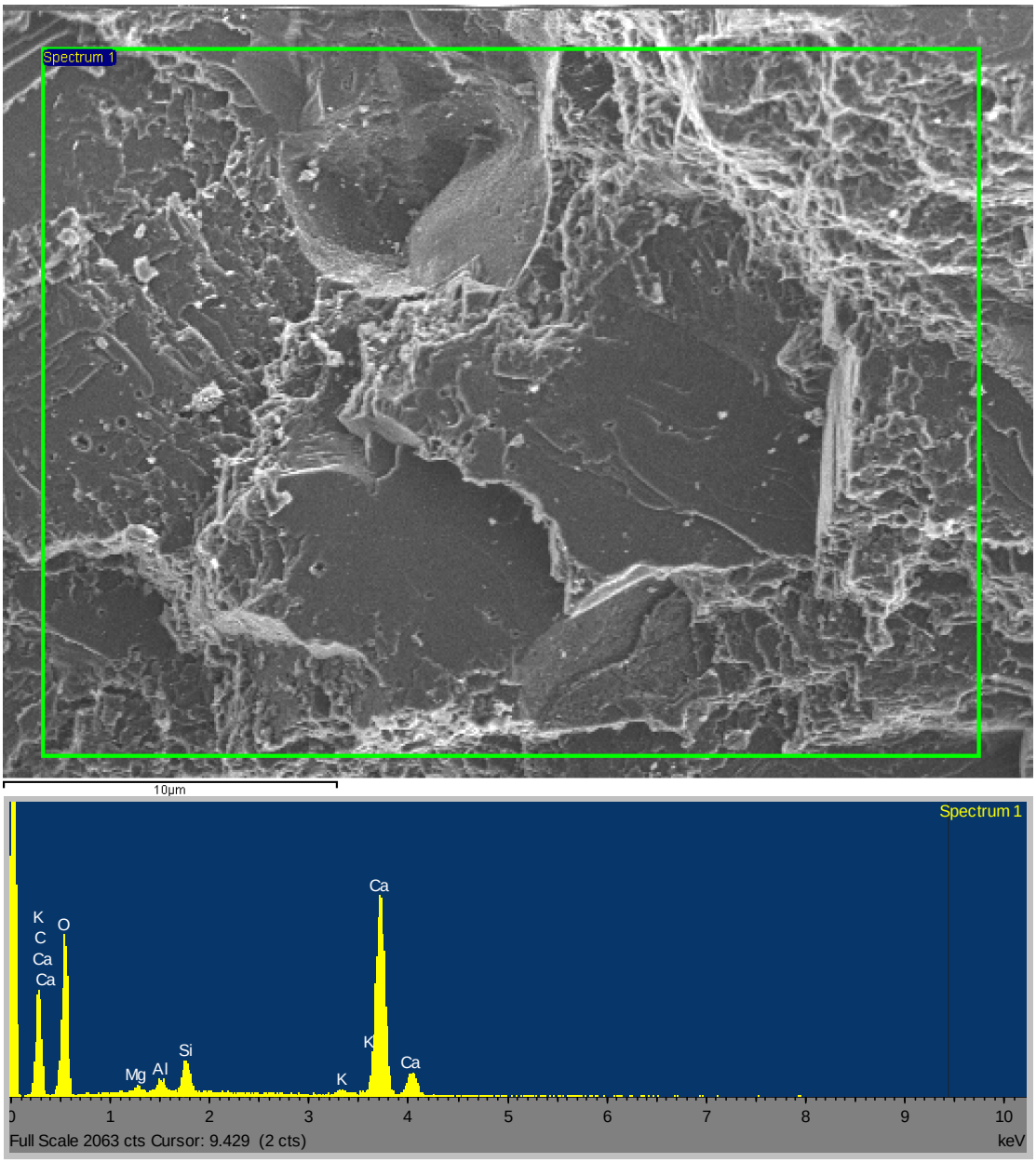
Element	O	Na	Al	Si	S	Cl	K	Ca	Total
Weight, %	50.46	2.11	2.49	7.48	1.11	3.50	1.55	31.30	100.00

Figure 4.48. SEM Micrograph and EDS Spectra of mix TM17.



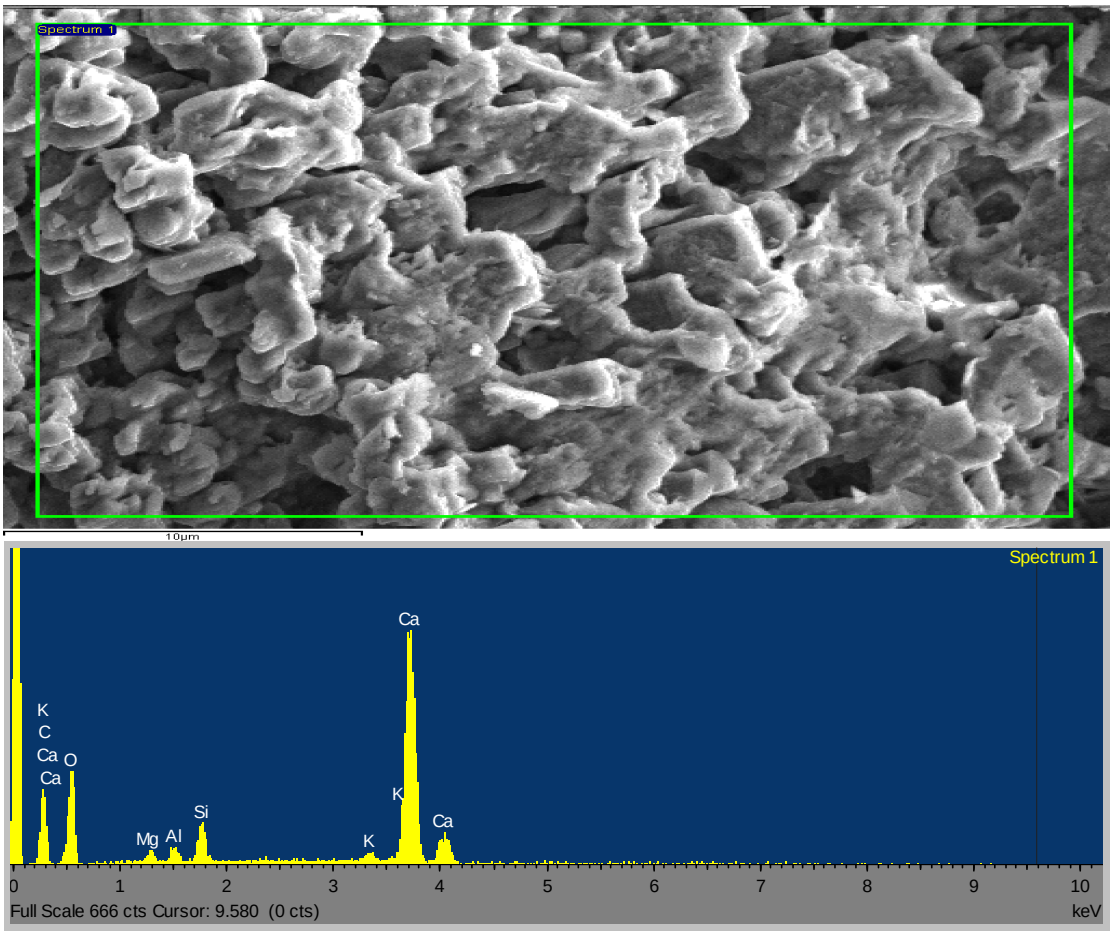
Element	O	Mg	Si	Ca	Br	Total
Weight, %	56.78	0.37	1.68	39.49	1.69	100.00

Figure 4.49. SEM Micrograph and EDS Spectra of mix TM17.



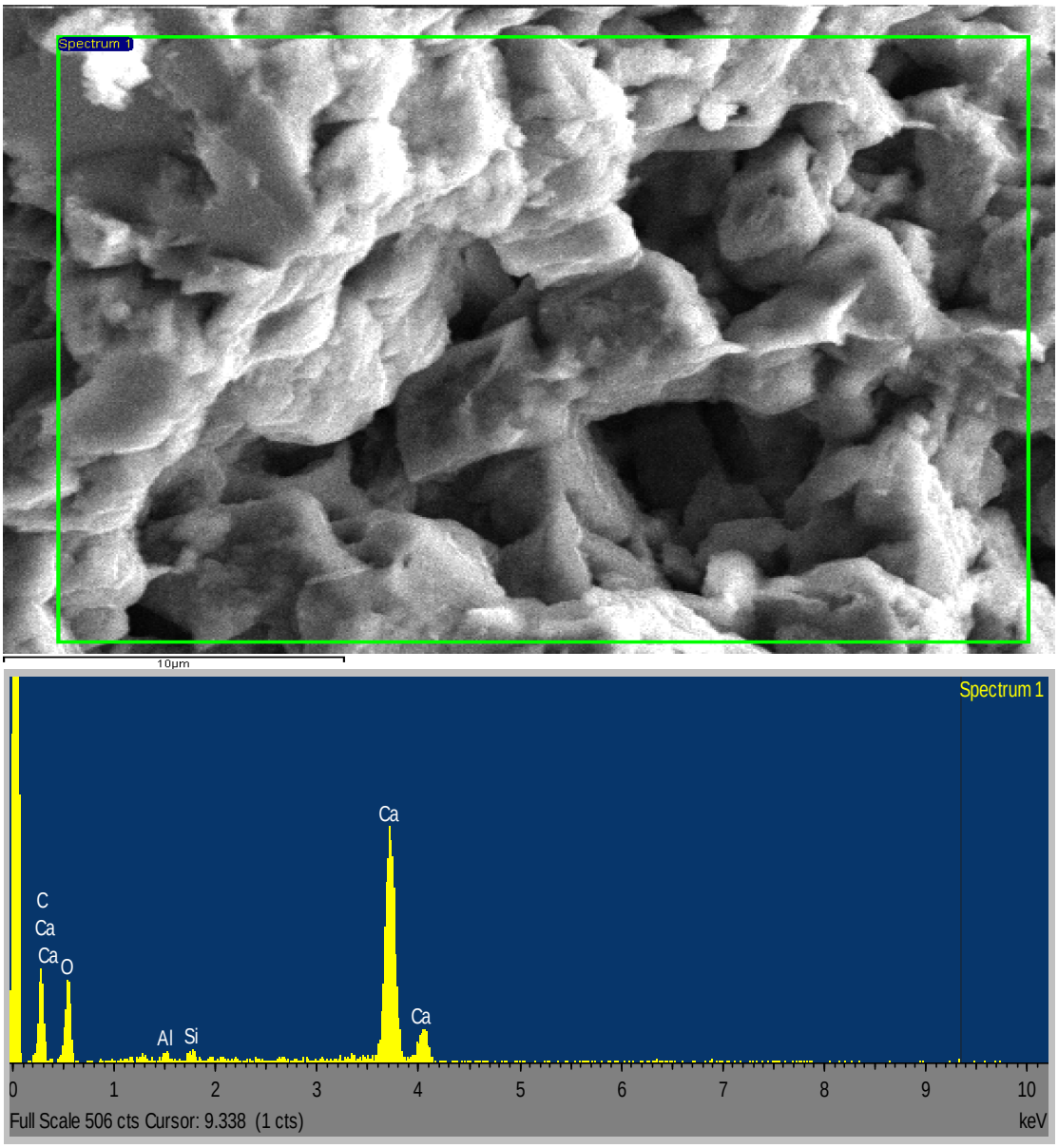
Element	O	Mg	Al	Si	K	Ca	Total
Weight, %	59.13	0.55	0.87	2.81	0.47	36.18	100.00

Figure 4.50. SEM Micrograph and EDS Spectra of mix TM17.



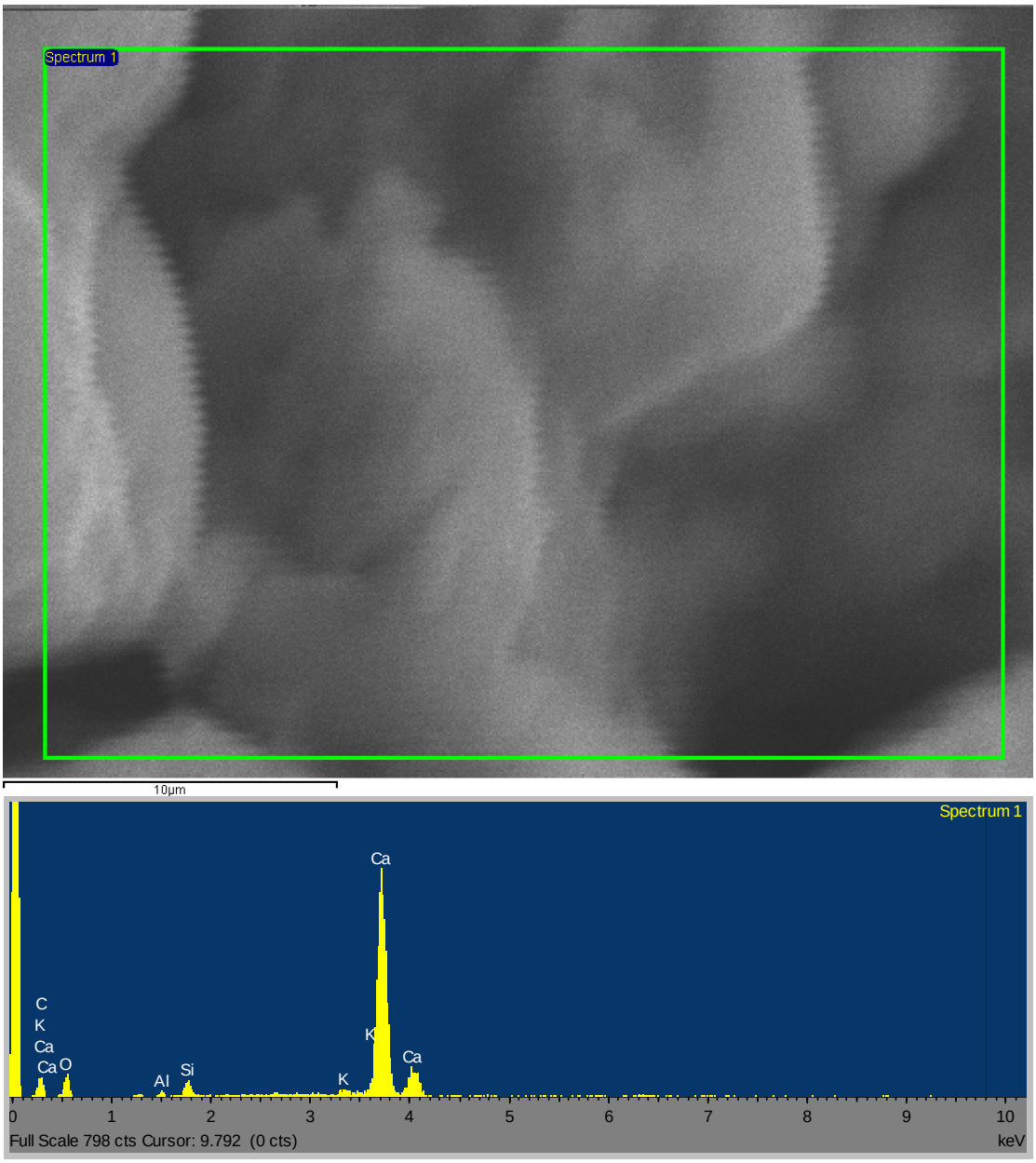
Element	O	Mg	Al	Si	K	Ca	Total
Weight, %	48.20	0.91	1.26	3.48	1.20	44.95	100.00

Figure 4.51. SEM Micrograph and EDS Spectra of mix TM20.



Element	O	Al	Si	Ca	Total
Spectrum 1	48.20	0.86	1.12	49.82	100.00

Figure 4.52. SEM Micrograph and EDS Spectra of mix TM20(Sample2).



Element	O	Al	Si	K	Ca	Total
Weight, %	26.79	0.79	2.26	1.05	69.11	100.00

Figure 4.53. SEM Micrograph and EDS Spectra of mix TM20(Specimen 3).

Table 4.39. Summary of SEM micrographs and EDS spectra of concrete specimens exposed to the tidal zone.

Specimen	Cement Type	Pozzolan	Sulfur Content (%)	Aluminum Content (%)	Sulfate Attack
TM1	I	None	1.02	1.29	Present
TM2	V	None	2.09-2.91	1.79-5.03	Present
TM7	I	8% SF	0	0.88-3.01	Absent
TM17	I	30% FA	1.11	0-2.49	Present
TM20	I	70% GGBFS	0	0.79-1.26	Absent

SF: Silica fume; FA: Fly ash; GGBS: Ground granulated blast furnace slag.

4.2 Partially Buried Specimens

4.2.1. Visual Observations

COLUMNS

There was no major noticeable deterioration in the columns exposed to the partially buried zone for 10 years. Fine shrinkage cracks were noticed in the finished mortar on the mid section of the columns. In the specimen with mixes BM3, BM7, BM15, and BM18, weathering of concrete was noted at the interface, possibly due to sulfate attack mostly towards the sea side face. Also, aggregate was found to be exposed in the specimen made of mix BM 17 at the interface. A typical photograph of a partially buried column is shown in Figure 4.54.

CYLINDERS

Noticeable deterioration was not noted onthe cylindrical specimens buried under ground for 10 years. Deposits of sand were seen on most of the specimens. While there was no change of color in most of the specimens greenish black deposits of oil was noted on few. Sand and clayey deposits had adhered strongly to the surfaces of almost all specimens. No major changes were noted on the specimens after ten-years exposure. Figure 4.55 shows cylindrical concrete specimens after ten years of below ground exposure.

CUBES

Noticeable deposits of sand were seen on all the cube specimens. The color of most of the specimens remained unchanged, while some changed to greenish black due to deposits of oil. Sand and clayey deposits adhered strongly to the surfaces of specimens. A typical photograph of specimens of this category is shown in Figure 4.56.

Figure 4.54. Photograph of a column specimen in the partially buried zone.

Figure 4.55. Concrete cylindrical specimens exposed to below ground conditions for 10 years.

Figure 4.56. Cube concrete specimens exposed to below ground conditions for 10 years.

4.2.2. Corrosion Potentials

The potential readings of the steel reinforced columns in this zone are presented in Tables 4.40 through 4.66. In general, the corrosion potentials in the AG portion are expected to be close to no corrosion range since this portion of the column exhibits a uniform exposure to the prevailing climatic and atmospheric condition. The interface and below ground portion of the column was not only exposed to soil and groundwater and more humid conditions but also to differential aeration around the interfacial area of the column. Thus, more negative corrosion potentials are expected in the interface and below ground portion of the column.

HALF-BURIED COLUMNS

In all the columns, the potentials on the above ground portion were less negative thanthose on the IF&BG portions. In mix BM1 (Type I cement), the average corrosion potentials in the IF&BG portion reached -361 mV CSE after 3,649 days, indicating 90% probability of active corrosion in this portion of the column.In the AG portion of the column, the potential was –127 mV CSE, indicating no active corrosion in this portion of the column. Under the conditions prevailing in the exposure zone, the IF&BG portion of the column moved to active corrosion state, whereas the AG portion of the column maintained its state of no active corrosion.

In mix BM2, columns with Type V cement, the average corrosion potentials in the IF&BG portions of the columnsreached -252 mV CSE after 3649 days indicating uncertain corrosion. The potential in above ground portion was –115 mV CSE, indicating no active corrosion state in this part of the column. The entire columns with Type V cement concrete performed very well from corrosion resisting aspect, and the corrosion potentials measured were in a state of no corrosion throughout the column.

The corrosion potentials in the specimen BM3, column with highquantity of Type I cement was about –294 mV CSE, indicating state of uncertain corrosion. The trend of the corrosion potentials in the upper portion of this colum was similar to that of specimen BM1, control column. The corrosion potential in the AG portion was -99 mV CSE indicating passive corrosion. Compared to potential in the control column, BM1, it is clear that increasedquantity of cement (450 kg/m^3 in BM3) improved the corrosion resistant of concrete.

In mixes BM4 and BM7, columns with silica fume (SF) cement, the beneficial effect of SF on corrosion resisting properties of concrete is clearly visible. The corrosion potentials in both the IF&BG and AG portions of column BM4,as shown inTables 4.49 to 4.54. The average corrosion potential in the IF&BG portion of the column was -89 mV CSE. The corrosion potential in the AG portion was -45 mV CSE, indicating no active corrosion.

Almost similar results were obtained in the columns of mix BM7.The corrosion potentials in both the IF&BG and AG portions of the column was -89 mV CSE, while in the above ground portion it remained at -48 mVCSE. As expected, the potentials in the AG portion of the column were less negative than those in the IF&BG portion of the column, indicating that the column was entirely in no active corrosion state. The less negative corrosion potentials measured in the columns BM4 and BM7 is attributable to the beneficial effect of lower w/(c+SF) ratio and SF in the concrete.

The trends of potential variation in the columns for mixes BM8 (8% FA), BM17 (30% FA) and BM15 (10% Superpozz) were very similar throughout the exposure period.In these mixes, namely BM8, BM15 and BM17, the average corrosion potential in the IF&BG portion of the column after 3,646 days were -127 mV, -88 mV, and -109 mV CSE, respectively indicating no active corrosion state. The average potentials in the AG portion of the column were -53mV, -56 mV, and -78 mV CSE, respectively, indicating state of no corrosion in these columns.

The beneficial effect of FA and Superpozz in enhancing the corrosion resistance of concrete is very clear from the reported results. The results also reflect the effect of quantity and fineness of these pozzolanic materials on enhancing the corrosion resistance of concrete.

In mix BM20, the average corrosion potential was -75 mV and -127 mV CSE, respecively, for IF&BG portions of the columns. These columns remained in passive state in terms of corrosion activity at the end of 10 years of exposure.

Table 4.40. Corrosion potentials on steel in half-buried column BM1-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-239	-226	-225	-234	-264	-76	-15	-199	-157	-128
B	-87	-80	-81	-91	-118	-151	-233	-425	-381	-357
C	-24	-17	-22	-37	-42	-68	-7	-158	-176	-135
D	-63	-80	-86	-104	-126	-150	-209	-415	-395	-370

Table 4.41. Corrosion potentials on steel in half-buried column BM1-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-102	-86	-89	-120	-147	-210	-285	-429	-480	-452
B	-116	-105	-104	-138	-157	-214	-290	-432	-469	-439
C	-111	-99	-107	-124	-147	-167	-215	-421	-501	-475
D	-116	-95	-108	-121	-147	-177	-216	-423	-485	-463

Table 4.42. Corrosion potentials on steel of half-buried column BM1-3.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-110	-105	-106	-115	-150	-198	-307	-546	-498	-501
B	-124	-117	-122	-139	-169	-201	-315	-527	-486	-479
C	-111	-106	-106	-129	-154	-202	-284	-270	-511	-500
D	-110	-109	-117	-138	-171	-206	-289	-545	-514	-501

Table 4.43. Corrosion potentials on steel of half-buried column BM2-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-107	-76	-102	-85	-111	-157	-197	-244	-177	-197
B	-157	-132	-145	-93	-116	-170	-211	-216	-180	-183
C	-33	-28	-34	-45	-60	-66	-114	-230	-218	-216
D	-33	-39	-42	-60	-40	-66	-115	-254	-236	-190

Table 4.44. Corrosion potentials on steel in half-buried column BM2-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-126	-132	-160	-169	-170	-191	-257	-356	-325	-326
B	-132	-141	-165	-173	-183	-197	-268	-369	-337	-320
C	-119	-108	-108	-110	-145	-181	-223	-383	-368	-357
D	-133	-107	-113	-116	-167	-172	-203	-394	-369	-375

Table 4.45. Corrosion potentials on steel of half-buried column BM2-3.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-99	-94	-115	-141	-118	-142	-169	-251	-234	-221
B	-113	-132	-149	-142	-121	-167	-211	-242	-241	-216
C	-87	-70	-64	-68	-78	-103	-141	-263	-264	-260
D	-65	-74	-90	-83	-81	-101	-178	-257	-274	-256

Table 4.46. Corrosion potentials on steel in half-buried column BM3-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-101	-95	-112	-136	-150	-186	-253	-413	-437	-399
B	-115	-113	-128	-156	-184	-226	-255	-409	-445	-441
C	-114	-113	-119	-130	-159	-186	-249	-442	-473	-451
D	-109	-99	-115	-132	-163	-208	-250	-424	-481	-46

Table 4.47. Corrosion potentials on steel in half-buried column BM3-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-53	-65	-61	-38	-45	-35	-67	-133	-155	-146
B	-21	-56	-22	-18	-18	-4	-76	-139	-126	-159
C	-77	-77	-57	-42	-29	-1	-97	-165	-202	-151
D	-62	-44	-35	-19	-4	-13	-64	-185	-216	-163

Table 4.48. Corrosion potentials on steel in half-buried column BM3-3.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-92	-87	-98	-125	-142	-158	-266	-388	-432	-411
B	-104	-89	-100	-120	-144	-163	-271	-387	-415	-407
C	-87	-102	-103	-120	-147	-187	-245	-387	-458	-411
D	-80	-92	-110	-135	-155	-177	-253	-394	-449	-422

Table 4.49. Corrosion potentials on steel in half-buried column BM4-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-41	-29	-22	-15	-24	-98	-123	-138	-135	-112
B	-141	-134	-130	-121	-142	-134	-151	-142	-124	-104
C	-48	-68	-56	-59	-60	-48	-59	-125	-130	-115
D	-63	-58	-51	-49	-45	-38	-50	-123	-161	-120

Table 4.50. Corrosion potentials on steel in half-buried column BM4-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-31	-30	-27	-33	-32	-27	-37	-59	-26	-21
B	-35	-31	-30	-34	-44	-31	-42	-49	-24	-23
C	-34	-11	-6	-23	-17	-45	-30	-128	-105	-84
D	-7	-5	-22	-17	-36	-67	-37	-134	-91	-64

Table 4.51. Corrosion potentials on steel in half-buried column BM4-3.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-45	-47	-48	-82	-91	-67	-99	-107	-107	-98
B	-43	-52	-55	-85	-109	-60	-79	-102	-83	-86
C	-17	-14	-25	-9	-7	-2	-50	-86	-113	-77
D	-20	-8	-2	-21	-1	-3	-29	-92	-123	-81

Table 4.52. Corrosion potentials on steel in half-buried column BM7-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-41	-29	-42	-39	-51	-59	-64	-81	-103	-98
B	-47	-46	-44	-47	-50	-85	-74	-97	-105	-98
C	-65	-64	-67	-59	-45	-28	-6	-90	-103	-100
D	-51	-62	-63	-58	-50	-31	-7	-91	-115	-101

Table 4.53.Corrosion potentials on steel in half-buried column BM7-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-39	-39	-35	-44	-29	-40	-57	-66	-84	-67
B	-45	-44	-48	-47	-26	-31	-53	-73	-86	-72
C	-55	-68	-63	-60	-48	-38	-16	-92	-104	-72
D	-67	-69	-67	-44	-46	-39	-7	-118	-113	-72

Table 4.54. Corrosion potentials on steel in half-buried column BM7-3.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-41	-47	-57	-70	-66	-70	-91	-127	-125	-118
B	-59	-56	-53	-65	-61	-81	-95	-142	-126	-132
C	-38	-33	-28	-32	-27	-15	-36	-132	-128	-115
D	-40	-47	-42	-30	-35	-23	-13	-159	-152	-116

Table 4.55. Corrosion potentials on steel in half-buried column BM8-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-60	-43	-59	-58	-44	-19	-101	-161	-123	-107
B	-64	-61	-70	-64	-36	-49	-113	-158	-111	-96
C	-45	-48	-45	-32	-8	-68	-102	-167	-152	-144
D	-50	-46	-40	-22	-7	-60	-112	-174	-162	-141

Table 4.56. Corrosion potentials on steel in half-buried column BM8-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-95	-92	-94	-91	-65	-25	-81	-140	-105	-107
B	-89	-82	-95	-86	-69	-42	-82	-132	-104	-111
C	-88	-94	-90	-79	-60	-16	-86	-130	-138	-119
D	-91	-91	-86	-72	-50	-5	-87	-119	-156	-131

Table 4.57. Corrosion potentials on steel in half-buried column BM8-3.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-59	-67	-55	-11	-4	-38	-109	-149	-140	-111
B	-56	-62	-56	-10	-11	-17	-118	-170	-155	-107
C	-58	-60	-59	-53	-30	-39	-111	-151	-140	-122
D	-53	-56	-51	-39	-22	-40	-103	-169	-171	-128

Table 4.58. Corrosion potentials on steel in half-buried column BM15-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-34	-49	-38	-25	-5	-19	-7	-121	-141	-85
B	-41	-55	-41	-1	-2	-1	-27	-110	-139	-89
C	-81	-84	-86	-76	-77	-66	-5	-148	-121	-109
D	-71	-71	-61	-59	-58	-37	-15	-89	-138	-111

Table 4.59. Corrosion potentials on steel in half-buried column BM15-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-35	-58	-71	-58	-46	-20	-62	-108	-90	-78
B	-41	-59	-53	-54	-46	-19	-50	-104	-99	-77
C	-99	-103	-89	-87	-77	-65	-6	-123	-113	-114
D	-100	-93	-81	-72	-59	-60	-9	-135	-140	-107

Table 4.60.Corrosion potentials on steel of half buried column BM15-3.

Period of Exposure, Days	Corrosion Potentials at Co-ordinates, mV CSE										
		1	2	3	4	5	6	7	8	9	10
3646	**A**	-40	-38	-40	-21	-47	-36	-23	-58	-139	-116
	B	-33	-55	-42	-21	-52	-38	-25	-62	-117	-99
	C	-91	-92	-86	-81	-71	-65	-11	-118	-108	-94
	D	-95	-86	-77	-67	-53	-49	-29	-144	-125	-91

Table 4.61. Corrosion potentials on steel in half-buried column BM17-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-120	-136	-128	-113	-91	-101	-19	-56	-94	-104
B	-113	-143	-135	-111	-100	-118	-8	-43	-102	-123
C	-116	-118	-108	-104	-81	-48	-76	-78	-129	-118
D	-125	-130	-121	-113	-97	-57	-56	-71	-133	-116

Table 4.62. Corrosion potentials on steel in half-buried column BM17-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-113	-124	-120	-137	-102	-95	-14	-36	-92	-100
B	-135	-131	-121	-111	-116	-100	-31	-56	-105	-96
C	-137	-128	-110	-101	-88	-60	-64	-78	-96	-90
D	-123	-121	-121	-122	-85	-55	-55	-72	-85	-90

Table 4.63. Corrosion potentials on steel in half-buried column BM17-3.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-127	-138	-131	-120	-80	-77	-4	-71	-108	-103
B	-121	-143	-141	-101	-46	-81	-3	-106	-107	-98
C	-137	-127	-118	-110	-91	-59	-31	-69	-130	-111
D	-128	-122	-121	-116	-85	-44	-49	-59	-122	-105

Table 4.64. Corrosion potentials on steel in half-buried column BM20-1.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-98	-79	-50	-5	-17	-43	-70	-112	-143	-122
B	-99	-80	-46	-32	-32	-59	-81	-132	-148	-133
C	-113	-107	-198	-62	-64	-31	-24	-118	-138	-121
D	-110	-105	-90	-80	-59	-26	-20	-118	-151	-126

Table 4.65. Corrosion potentials on steel in half-buried column BM20-2.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-144	-145	-141	-146	-130	-198	-118	-80	-95	-61
B	-144	-151	-146	-150	-133	-95	-23	-87	-91	-56
C	-141	-133	-126	-116	-89	-55	-13	-64	-79	-67
D	-136	-129	-124	-111	-87	-57	-11	-72	-87	-67

Table 4.66.Corrosion potentials on steel in half-buried column BM20-3.

Corrosion Potentials at Co-ordinates, mV CSE										
	1	2	3	4	5	6	7	8	9	10
A	-31	-34	-29	-21	-20	-4	-38	-141	-179	-145
B	-29	-36	-32	-24	-27	-3	-32	-140	-165	-134
C	-52	-47	-41	-28	-13	-16	-33	-258	-373	-471
D	-50	-46	-39	-31	-13	-16	-24	-227	-398	-486

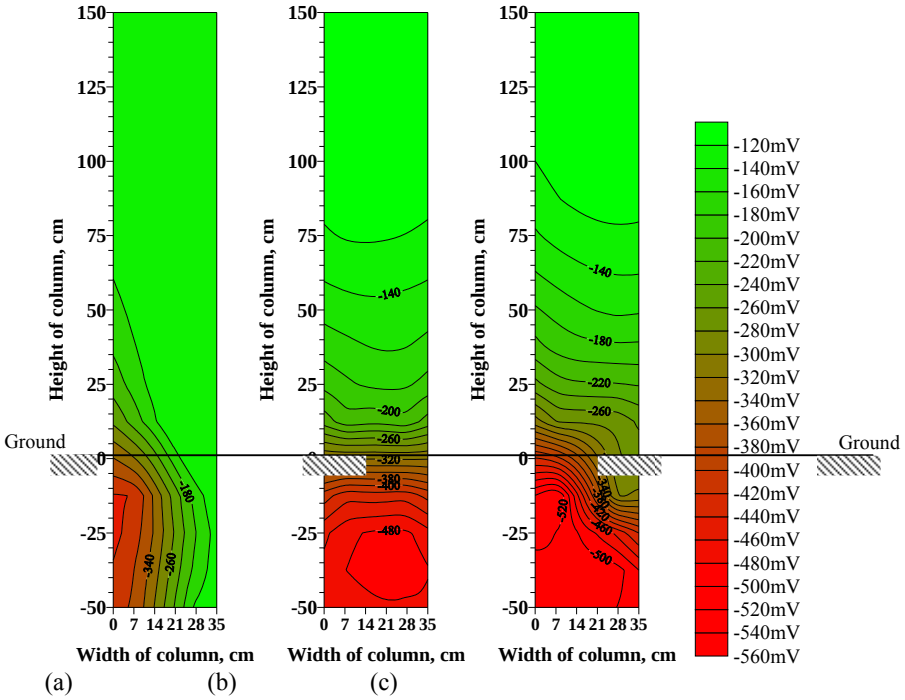


Figure 4.57. Corrosion potential contours in column specimens (a) BM1-1, (b) BM1-2, and (c) BM1-3 facing inland.

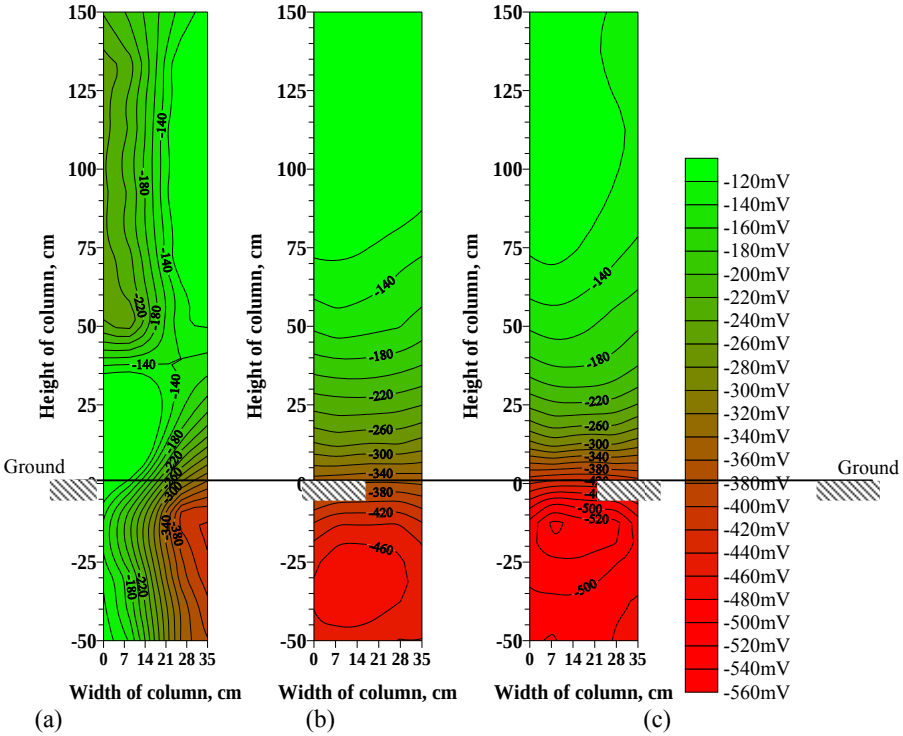


Figure 4.58. Corrosion potential contours in column specimens (a) BM1-1, (b) BM1-2, and (c) BM1-3 facing sea.

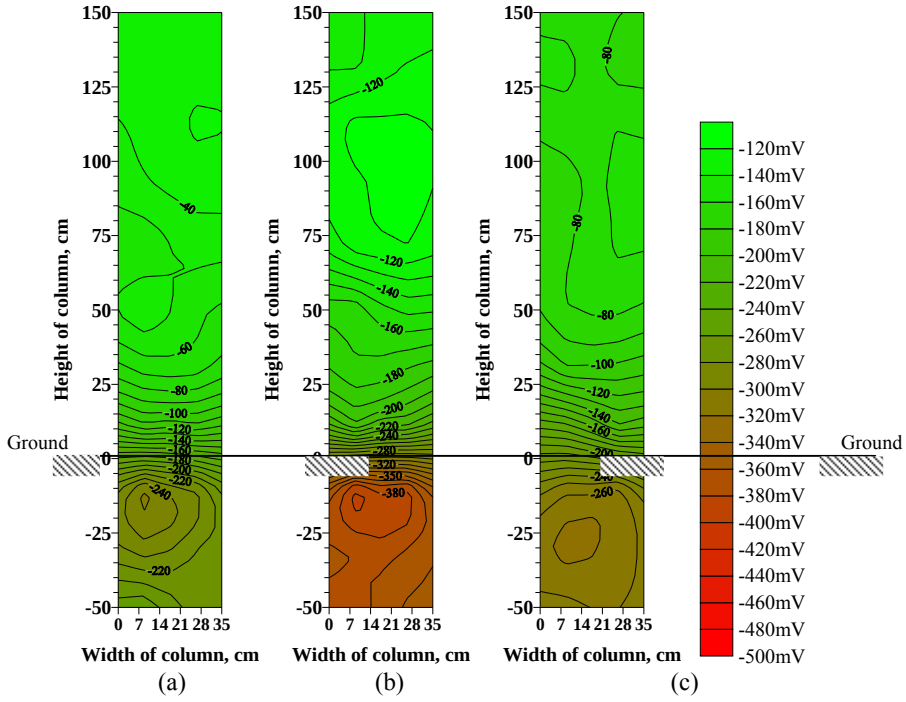


Figure 4.59. Corrosion potential contours in column specimens (a) BM2-1, (b) BM2-2, and (c) BM2-3 facing inland.

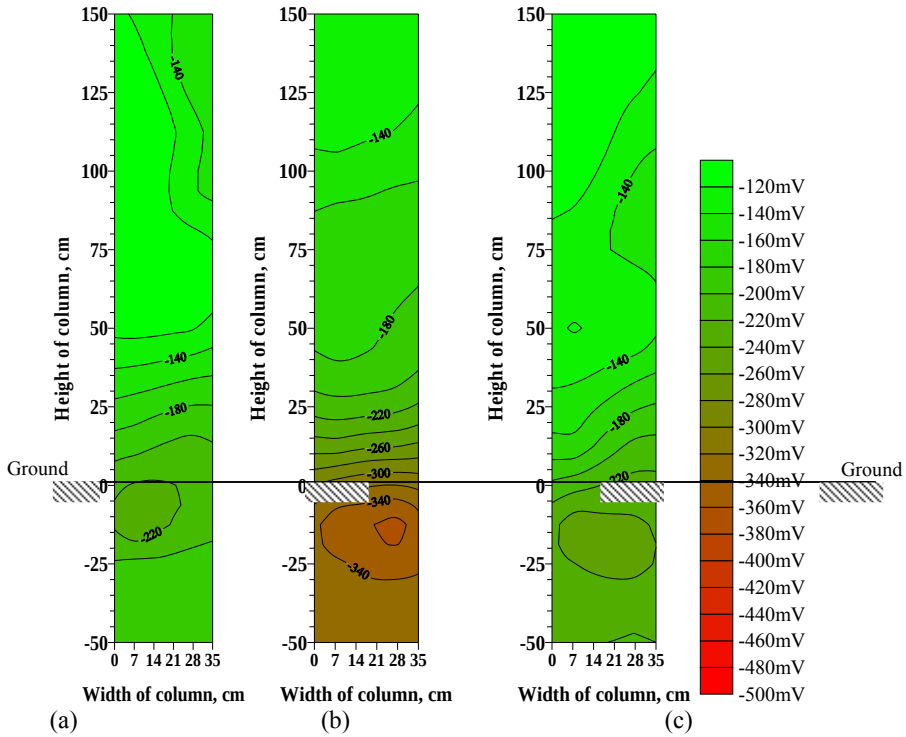


Figure 4.60. Corrosion potential contours in column specimens (a) BM2-1, (b) BM2-2, and (c) BM2-3 facing sea.

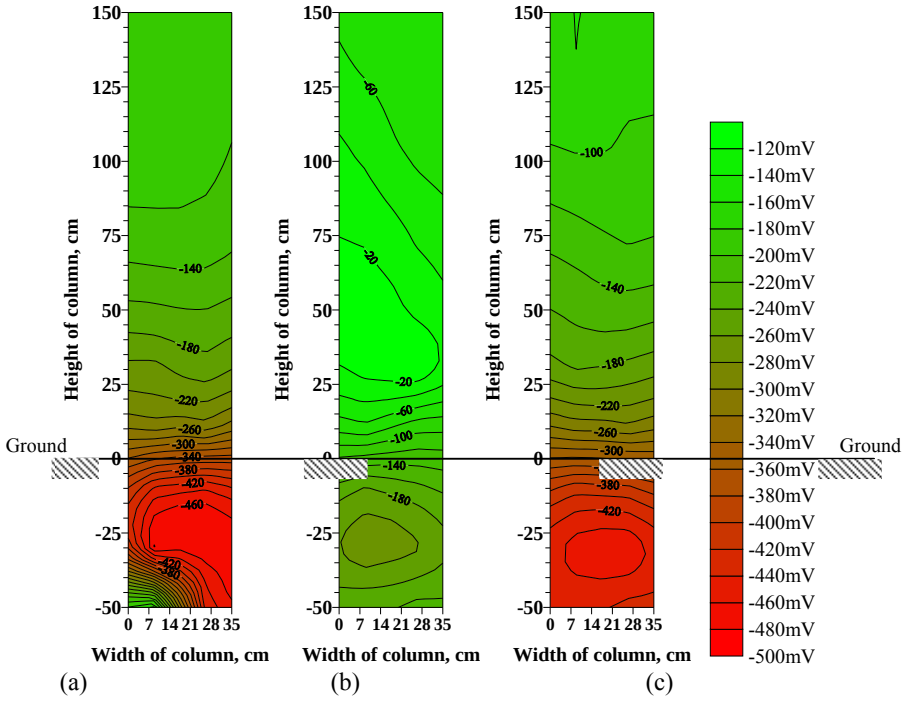


Figure 4.61. Corrosion potential contours in column specimens (a) BM3-1, (b) BM3-2, and (c) BM3-3 facing inland.

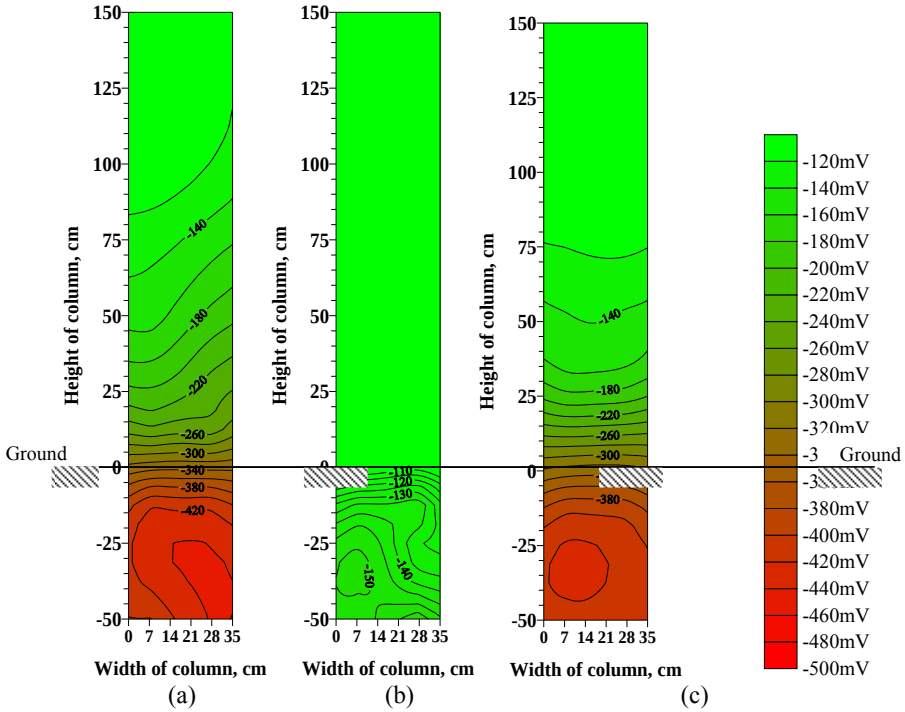


Figure 4.62. Corrosion potential contours in column specimens (a) BM3-1, (b) BM3-2, and (c) BM3-3 facing sea.

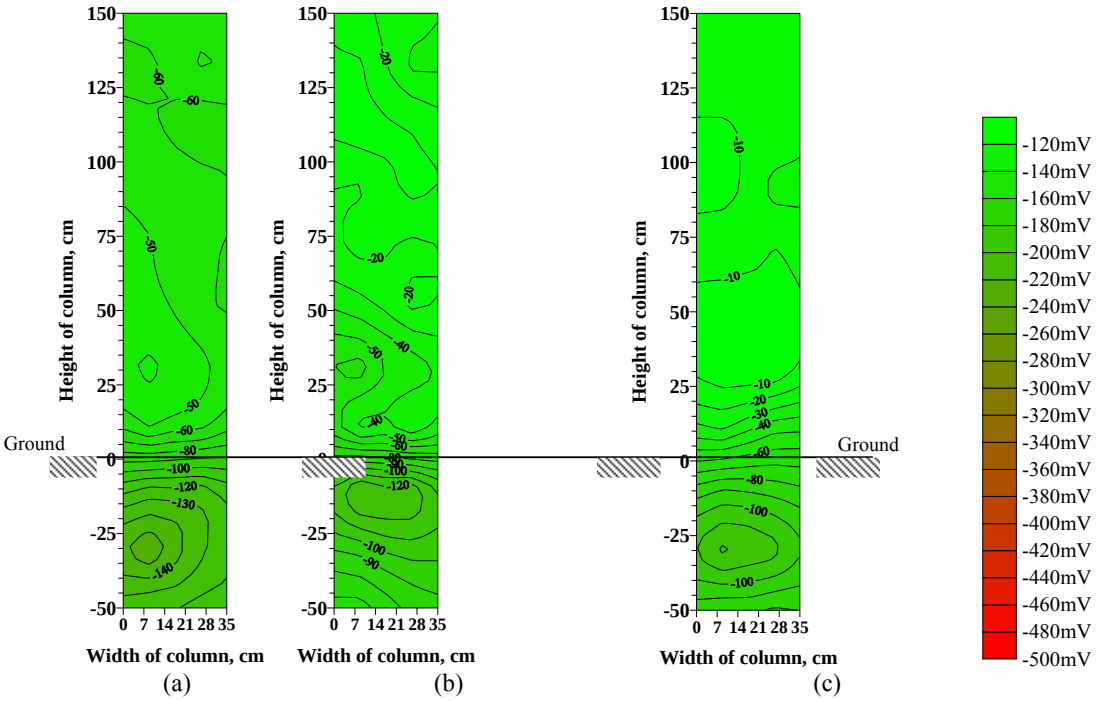


Figure 4.63. Corrosion potential contours in column specimens (a) BM4-1, (b) BM4-2, and (c) BM4-3 facing inland.

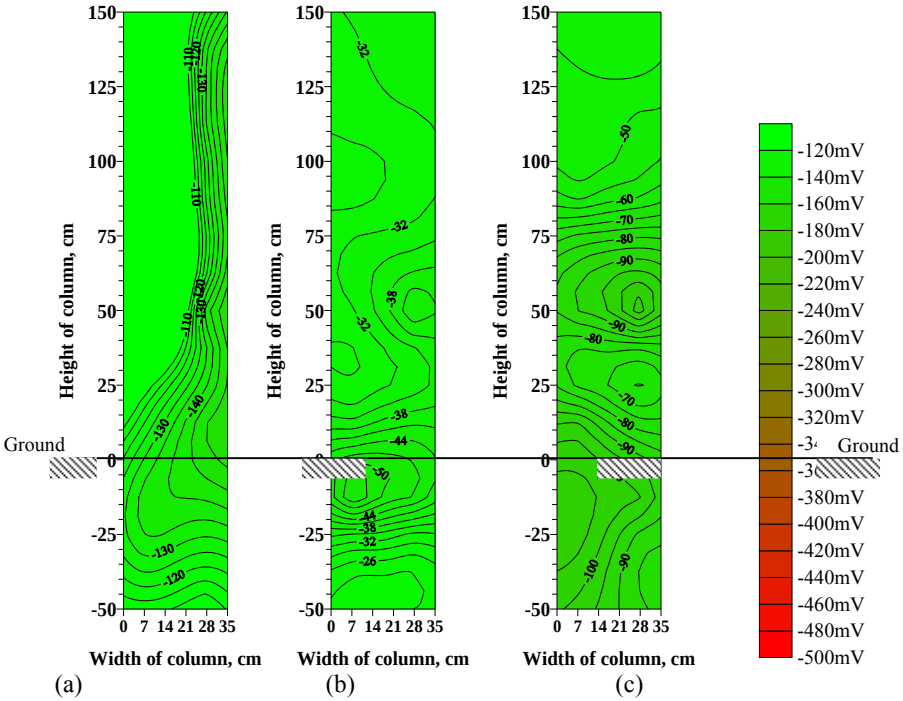


Figure 4.64. Corrosion potential contours in column specimens (a) BM4-1, (b) BM4-2, and (c) BM4-3 facing sea.

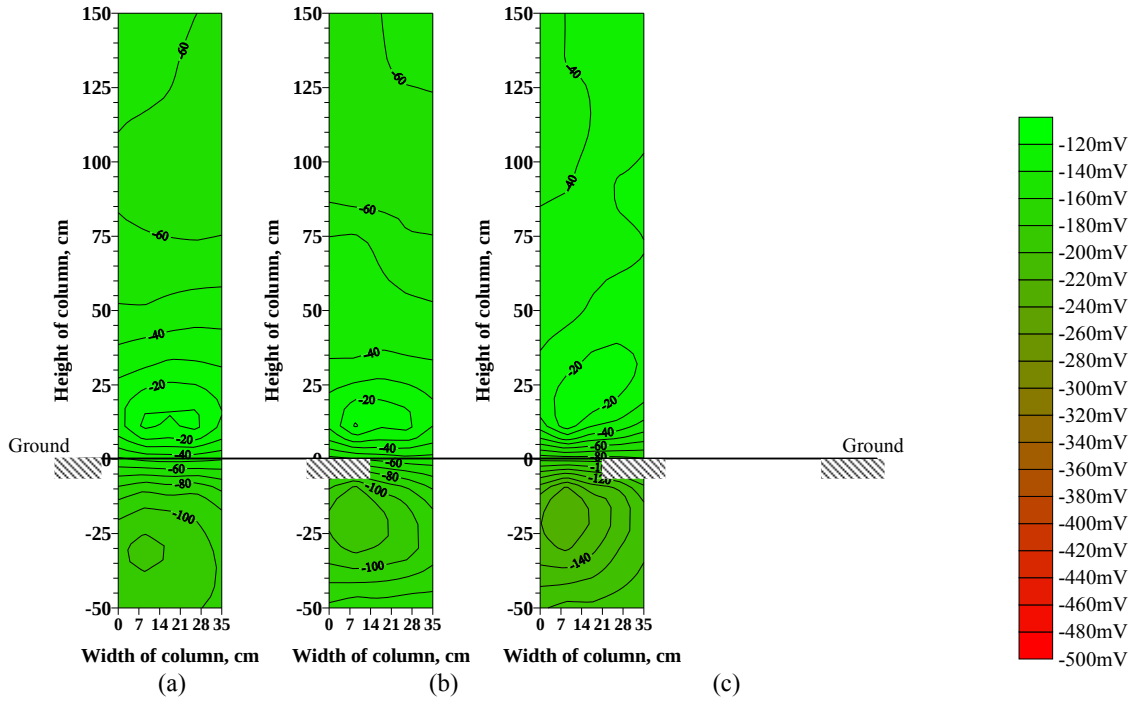


Figure 4.65. Corrosion potential contours in column specimens (a) BM7-1, (b) BM7-2, and (c) BM7-3 facing inland.

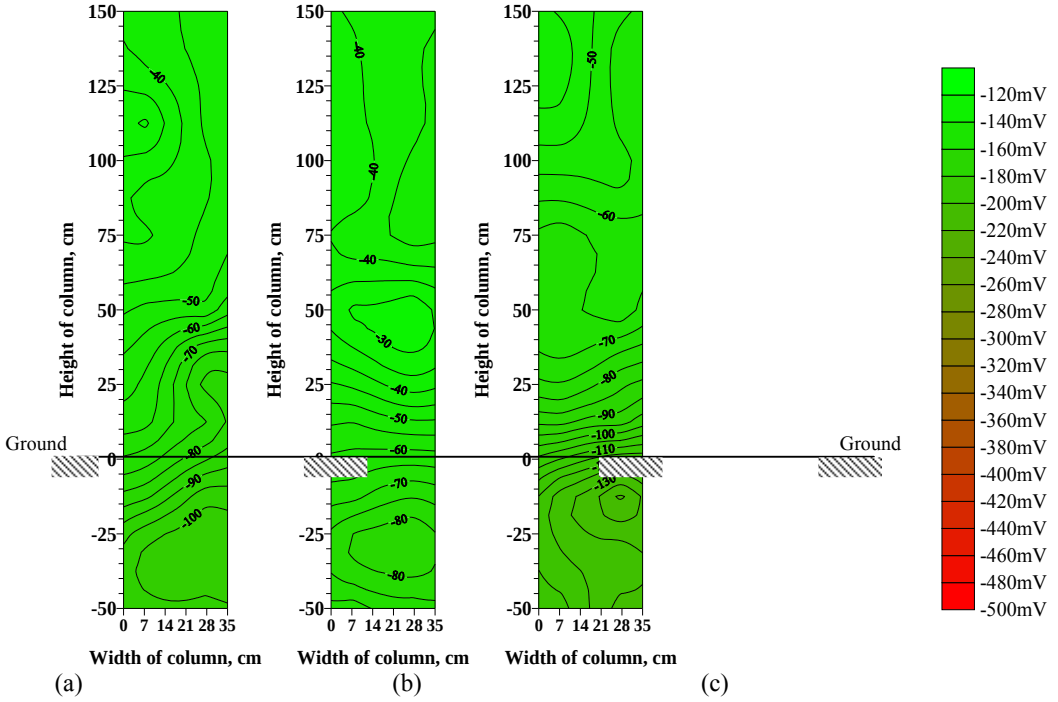


Figure 4.66. Corrosion potential contours in column specimens (a) BM7-1, (b) BM7-2, and (c) BM7-3 facing sea.

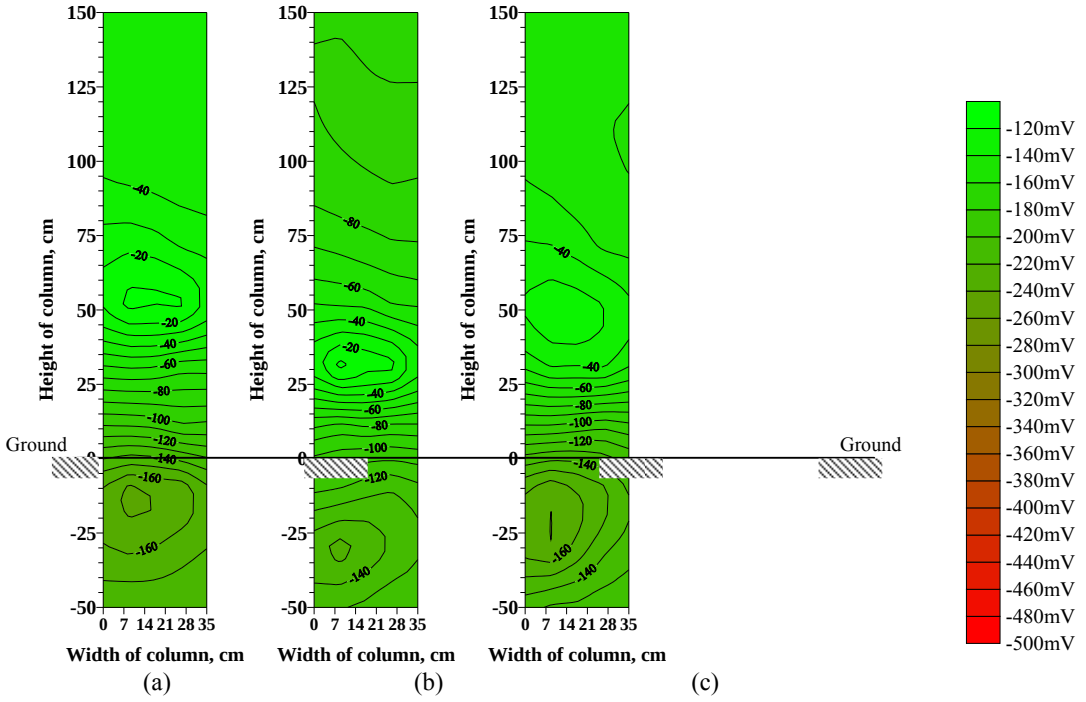


Figure 4.67. Corrosion potential contours in column specimens (a) BM8-1, (b) BM8-2, and (c) BM8-3 facing inland.

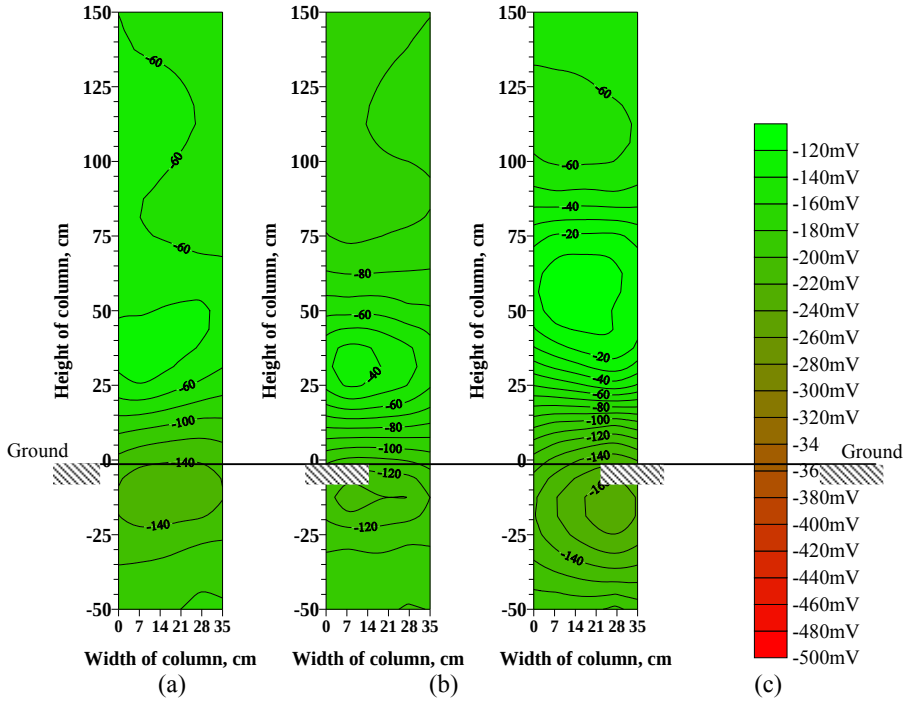


Figure 4.68. Corrosion potential contours in column specimens (a) BM8-1, (b) BM8-2, and (c) BM8-3 facing sea.

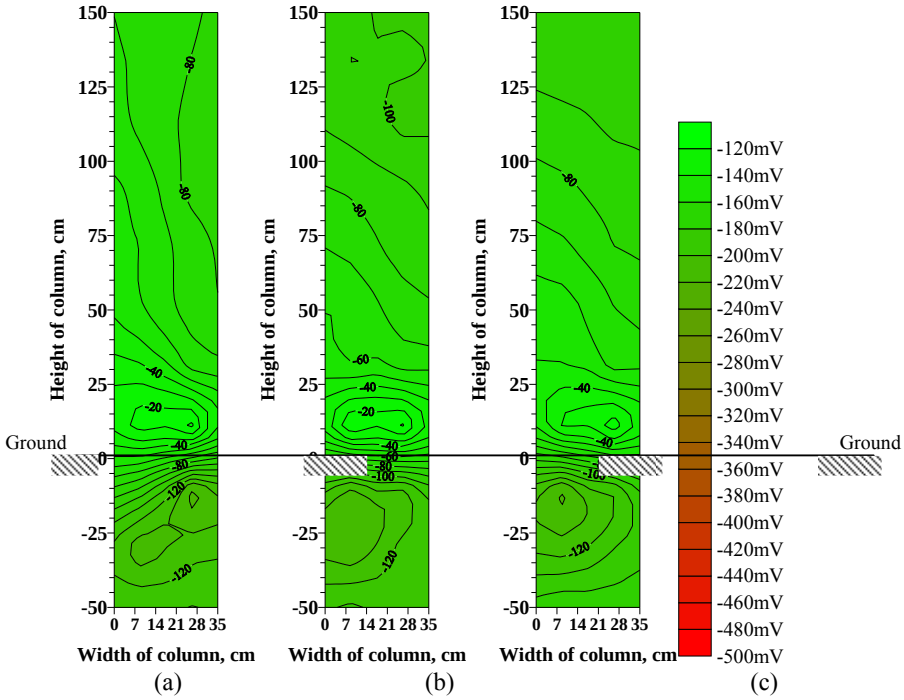


Figure 4.69. Corrosion potential contours in column specimens (a) BM15-1, (b) BM15-2, and (c) BM15-3 facing inland.

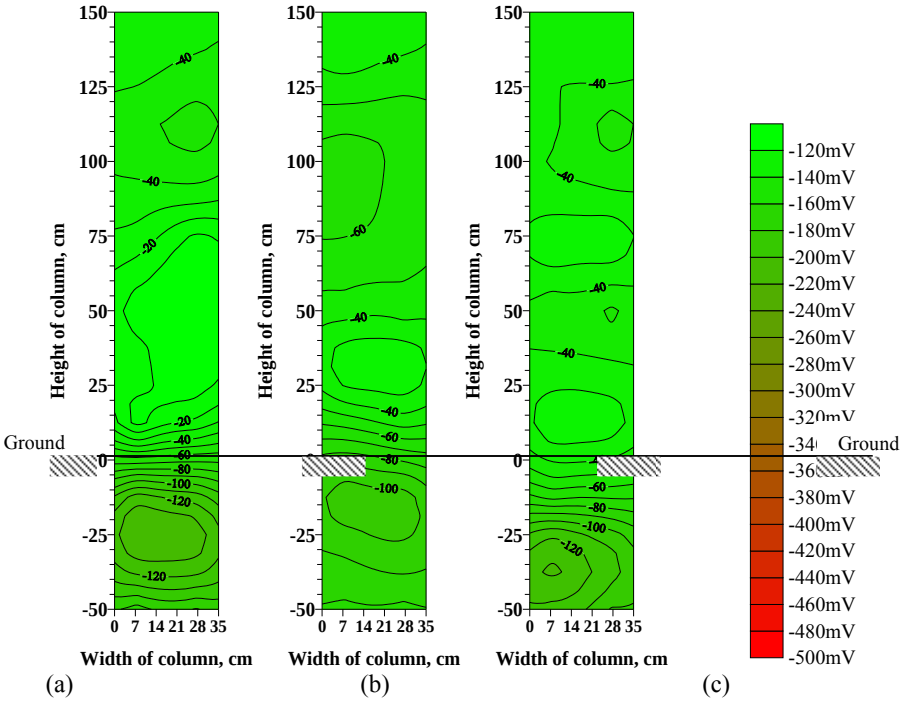


Figure 4.70. Corrosion potential contours in column specimens (a) BM15-1, (b) BM15-2, and (c) BM15-3 facing sea.

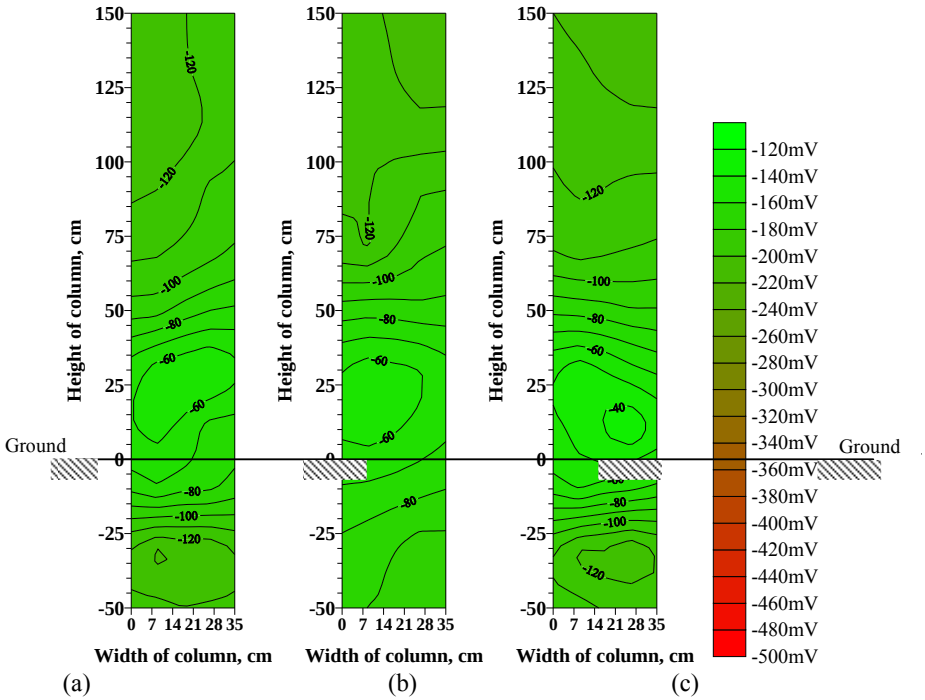


Figure 4.71. Corrosion potential contours in column specimens (a) BM17-1, (b) BM17-2, and (c) BM17-3 facing inland.

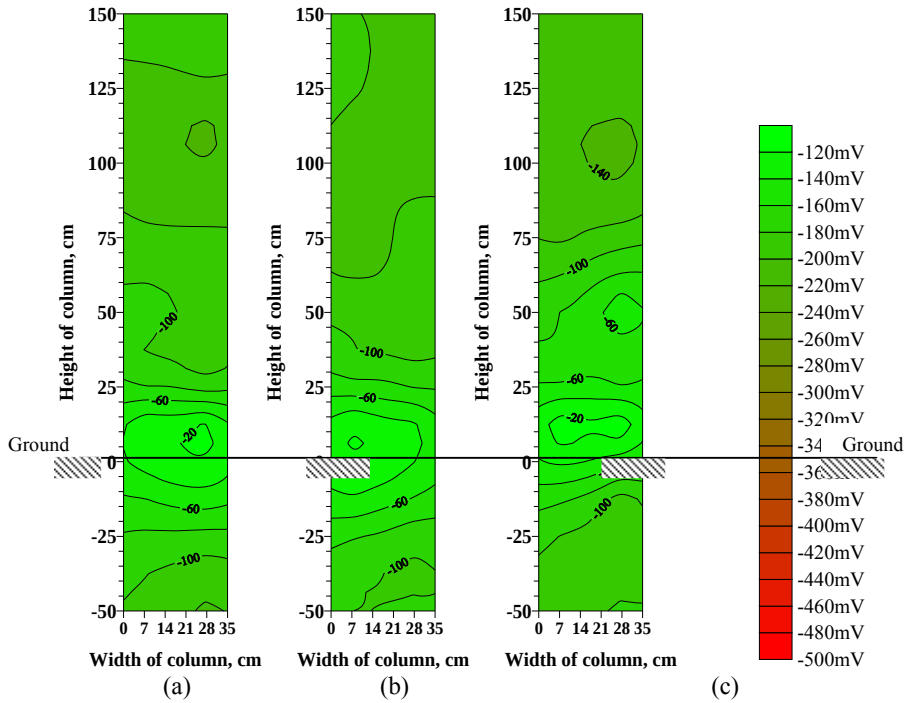


Figure 4.72. Corrosion potential contours in column specimens (a) BM17-1, (b) BM17-2, and (c) BM17-3 facing sea.

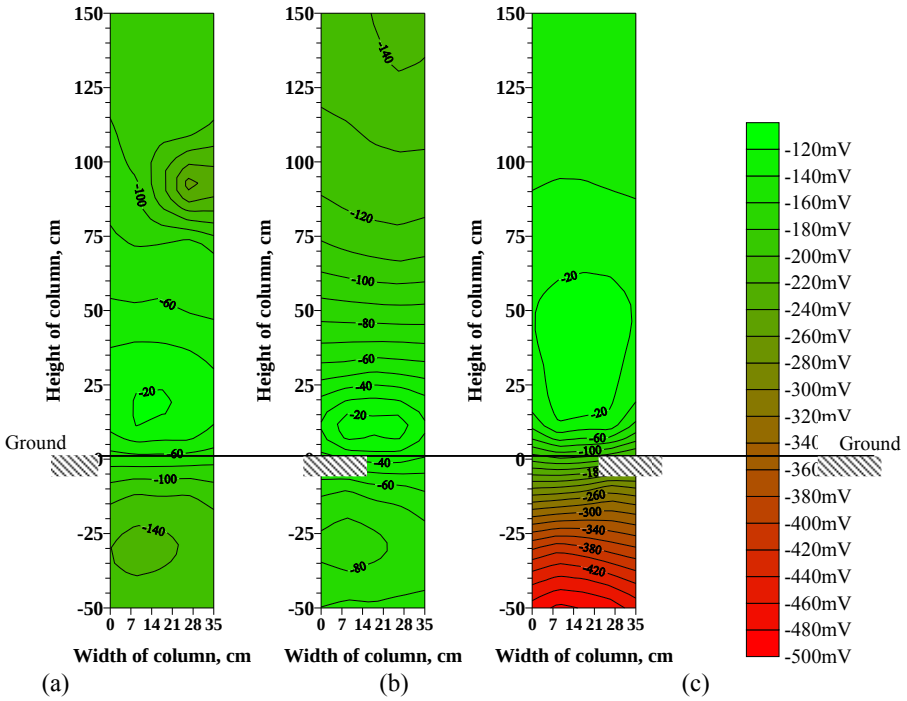


Figure 4.73. Corrosion potential contours in column specimens (a) BM20-1, (b) BM20-2, and (c) BM20-3 facing inland.

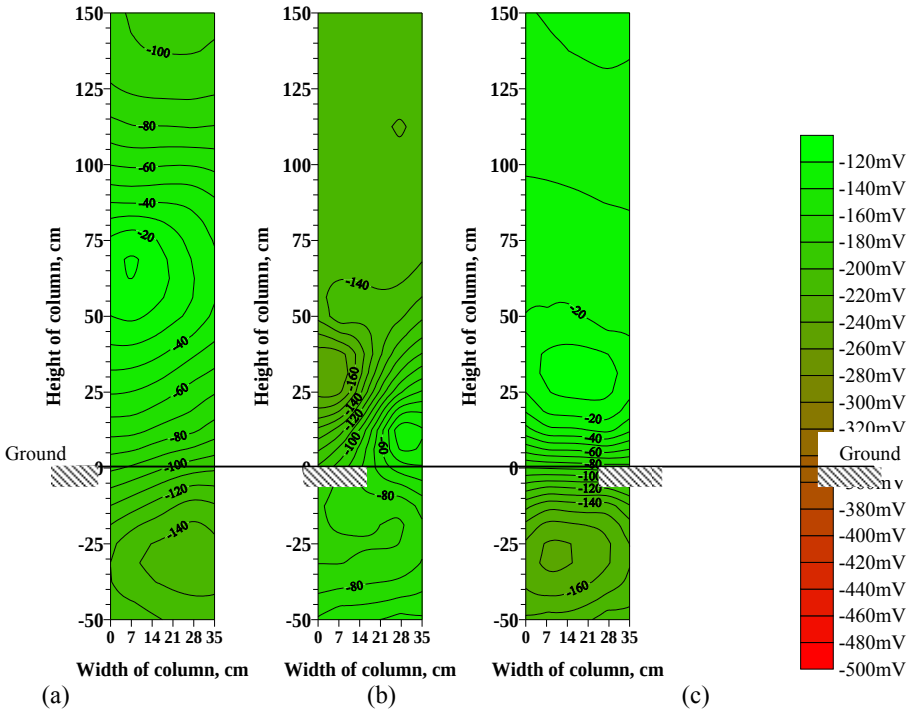


Figure 4.74. Corrosion potential contours in column specimens (a) BM20-1, (b) BM20-2, and (c) BM20-3 facing sea.

4.2.3. Chloride Concentration

The chloride concentration in the concrete specimens in below ground portion of the partially buried columns is summarized in Table 4.67 and depicted in Figure 4.75. The chloride concentration at the rebar level is plotted in Figure 4.76. The average chloride concentration at the rebar level is between 0.004% and 0.078%, by weight of concrete (i.e. 0.024% and 0.47% by weight of cement). The chloride concentration at the rebar level in three of the nine mixes exceeded the threshold chloride value of 0.025% by weight of concrete (i.e. 0.15% by weight cement).

Table 4.67.Chloride concentration in the below ground portion of the partially buried columns.

Mix #	Chloride ion concentration , % by wt. of concrete				
	0-5 mm	10-15 mm	25-30 mm	72-77 mm	95-100 mm
BM1	0.258	0.202	0.186	0.078	0.055
BM2	0.172	0.105	0.066	0.020	0.009
BM3	0.115	0.092	0.056	0.012	0.009
BM4	0.105	0.074	0.032	0.026	0.020
BM7	0.187	0.089	0.014	0.014	0.010
BM8	0.222	0.186	0.072	0.052	0.052
BM15	0.134	0.092	0.050	0.022	0.020
BM17	0.238	0.157	0.081	0.004	0.020
BM20	0.182	0.070	0.042	0.023	0.022

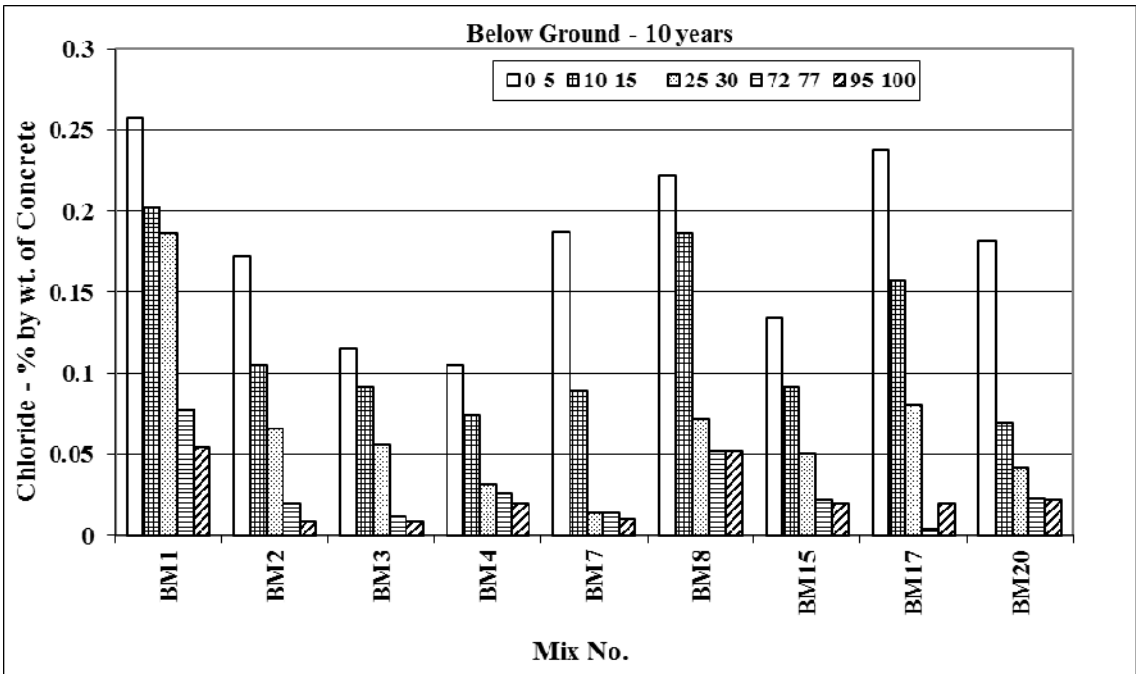


Figure 4.75.Chloride concentration profiles in below ground portion of partially buried columns.

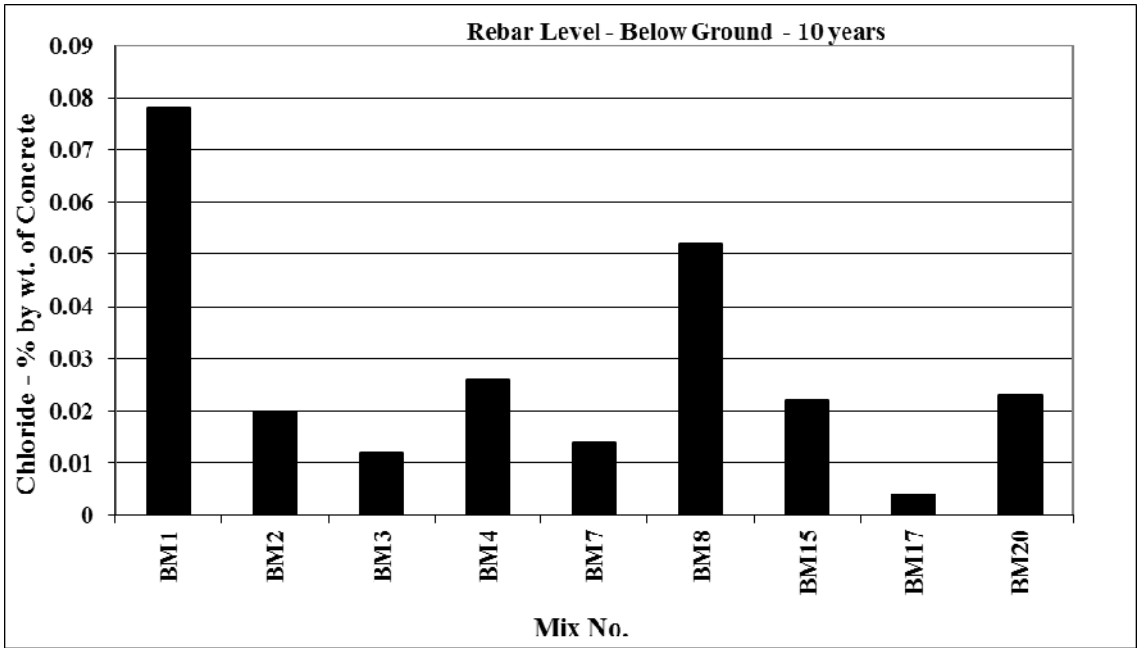


Figure 4.76. Chloride concentration at the rebar level in below ground portion of partially buried columns.

4.2.4. Sulfate Concentration

The sulfate concentration is summarized in Tables 4.68 and depicted in Figures 4.77.The results of sulfate concentration decreased with depth in all the specimens indicating that they have diffused from the service environment.

The average sulfate concentration in the surface layer of all the specimens ranged from 0.149% to 0.293% by weight of concrete (0.894% and 1.758% by weight of cement). The pozzolanic mixes do not show any advantage in terms of diffusion of sulfate ions. At the rebar level (72-77 mm), the sulfate concentration in the pozzolanic mixes in the below ground portion ranged between 0.086% and 0.121%.

Table 4.68. Sulfate concentration in the below ground portion of the partially buried columns.

Mix #	Sulfate ion concentration, % by wt. of concrete				
	Depth, mm				
	0-5	**10-15**	**25-30**	**72-77**	**95-100**
BM1	0.199	0.149	0.110	0.096	0.086
BM2	0.210	0.189	0.157	0.133	0.094
BM3	0.170	0.125	0.125	0.098	0.088
BM4	0.162	0.125	0.120	0.117	0.110
BM7	0.189	0.165	0.141	0.101	0.094
BM8	0.221	0.181	0.149	0.117	0.086

BM15	0.125	0.142	0.094	0.086	0.086
BM17	0.149	0.189	0.149	0.121	0.100
BM20	0.293	0.155	0.125	0.117	0.102

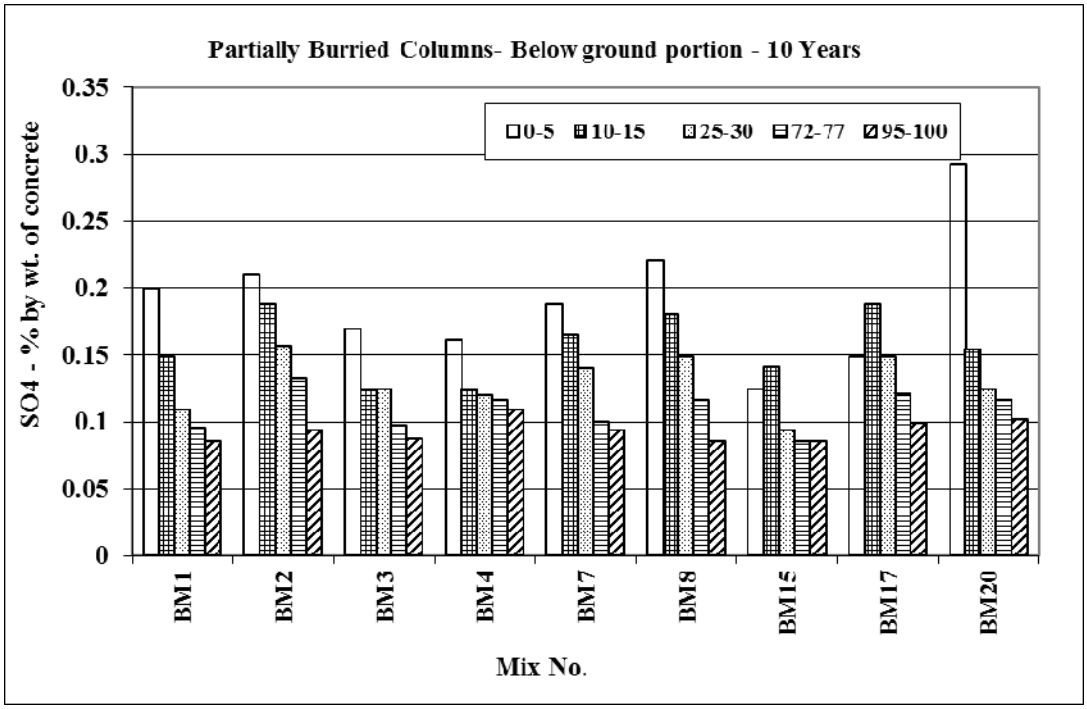


Figure 4.77.Sulfate concentration in the below ground portion of partially buried columns.

4.2.5 pH

The pH values in the belowground and above ground portions of the partially buried columns are summarized in Table 4.69 and depicted in Figure 4.78.The pH values at the exterior layer (i.e. 0 to 5 mm) of the below ground portion of the partially buried columns ranged from 11.56 to 12.28 while in the above ground portion the pH values ranged from 11.08 to 12.08.

Table 4.69. pH profile of the below ground portion of the partially buried columns.

Mix #	**pH**				
	Depth, mm				
	0-5	**10-15**	**25-30**	**72-77**	**95-100**
BM1	11.62	12.28	12.28	12.33	12.35
BM2	12.28	12.35	12.40	12.40	12.4
BM3	12.28	12.33	12.33	12.38	12.44
BM4	12.28	12.29	12.37	12.36	12.38
BM7	11.92	12.08	12.12	12.24	12.24
BM8	11.68	11.78	11.86	11.92	11.98
BM15	12.23	12.26	12.31	12.33	12.36
BM17	11.86	11.88	11.98	12.00	12.04
BM20	11.56	11.58	11.62	11.79	12.04

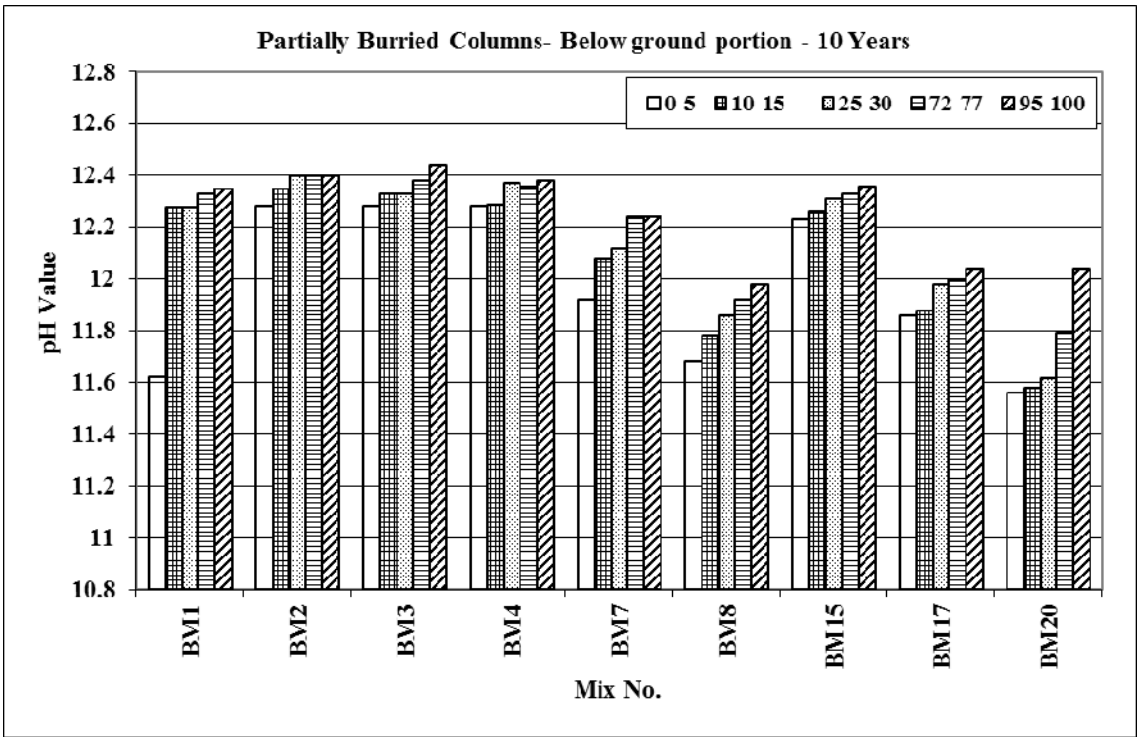


Figure 4.78.pH profile in the below ground portion of partially buried columns.

4.2.6 Water Permeability

The water permeability values for the below ground portions of the all the specimens are summarized in Table 4.70and depicted in Figure 4.79. The water permeability of mixes M4 (High cement content, low w/c ratio and 8% SF), M7 (8% SF), M15 (10% Superpozz) and M17 (30 FA) was similar. However, the best mix in this zone was M15 (10% Superpozz) with a water permeability of 1.8 cm.

Table 4.70. Water permeability of the specimens exposed to below ground portions.

Mix #	Water permeability, cm
M1	7.5
M2	7.8
M3	7.4
M4	3.2
M7	3.9
M8	1.7
M15	1.8

M17	2.3
M20	5.6

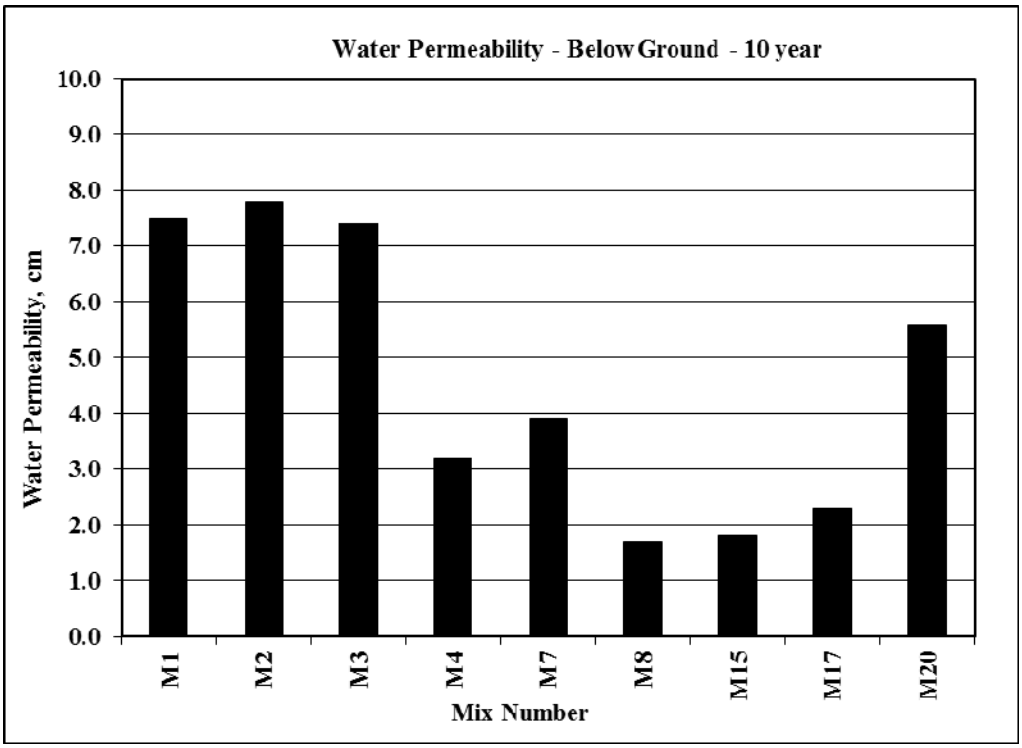


Figure 4.79. Water permeability of specimens placed in the below ground zone.

4.2.7. Chloride Permeability

The chloride permeability values are summarized in Table 4.71 and plotted in Figure 4.80. The chloride permeability values were in the low to very low range in all the mixes, except in mix M2 (Type V cement) in which the chloride permeability was in a moderate range.

Table 4.71. Chloride permeability in the belowground zone of partially buried columns.

Mix #	Chloride permeability, Coulombs
BM1	551.3
BM2	3354.3
BM3	710.3
BM4	117.0
BM7	109.7

BM8	164.0
BM15	144.7
BM17	348.7
BM20	97.0

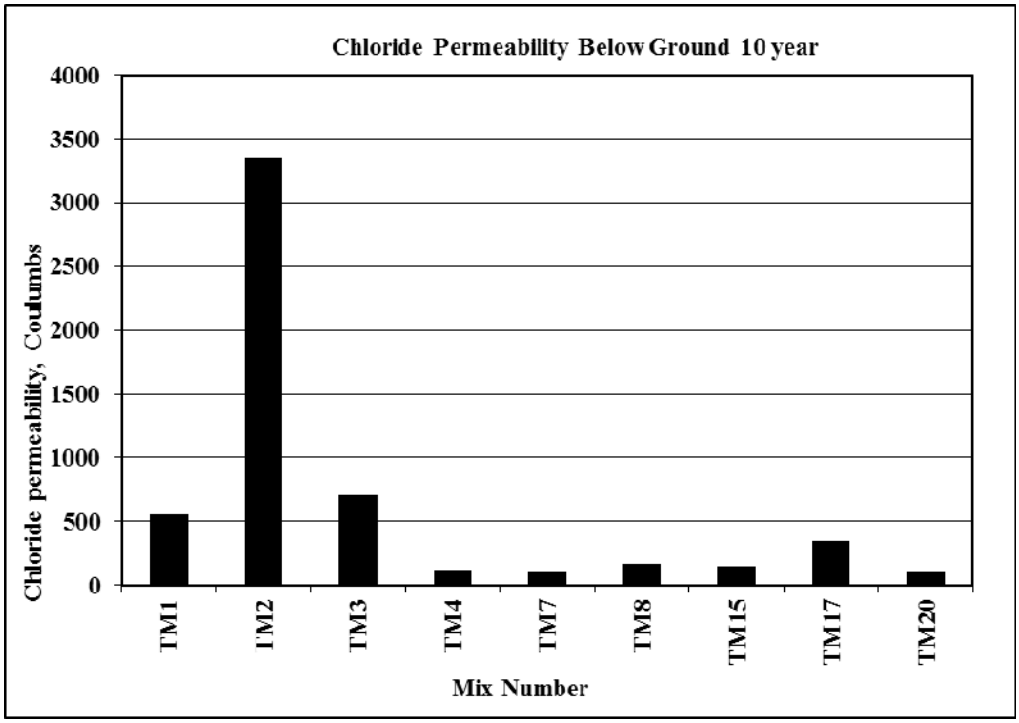


Figure 4.80.Chloride permeability of concrete specimens placed in the below ground zone.

4.2.8 Electrical Resistivity

Typical moisture content and electrical resistivity relationship is given in Figure. 4.81. The electrical resistivity results at initial and 3% moisture content of the concrete specimens exposed to below ground conditions are presented in Figures 4.82and 4.83, respectively.

The initial electrical resistivity was in the range of 41.12 kOhm.cm to 304.59 kOhm.cm. The pozzolanic concrete mixes, such as Mixes M7 (8% Silica fume), M8 (20% FA), M15 (10% Superpozz) and M20 (70% GGBFS) exhibited high initial electrical resistivity of more than 100 kOhm.cm indicating negligible risk of corrosion. Similarly, at 3% moisture content the electrical resistivity values of the concrete mixes with pozzolanic materials was less than that of the plain cement concrete specimens, the resistivity values being more than 100 kOhm.cm.

Further, the electrical resistivity of Mix M1 (Type I cement) was more than that of mix M2 (Type V cement) at both the initial and 3% moisture content.

Table 4.72. Electrical resistivity at initial moisture content.

Mix #	Moisture content, %	Electrical resistivity, kOhm.cm
M1	2.66	134.63
M2	2.67	52.61
M3	3.10	55.71
M4	3.02	154.68
M7	3.71	146.06
M8	3.19	210.58
M15	2.80	195.15
M17	2.84	56.68
M20	4.11	326.09

Table 4.73.Electrical resistivity at a moisture content of 3%.

Mix #	Electrical Resistivity, kOhm.cm
BM1	104.85
BM2	44.72
BM3	57.4
BM4	180.77
BM7	304.59
BM8	299.63
BM15	159.36
BM17	41.12
BM19	80.54
BM20	179.42

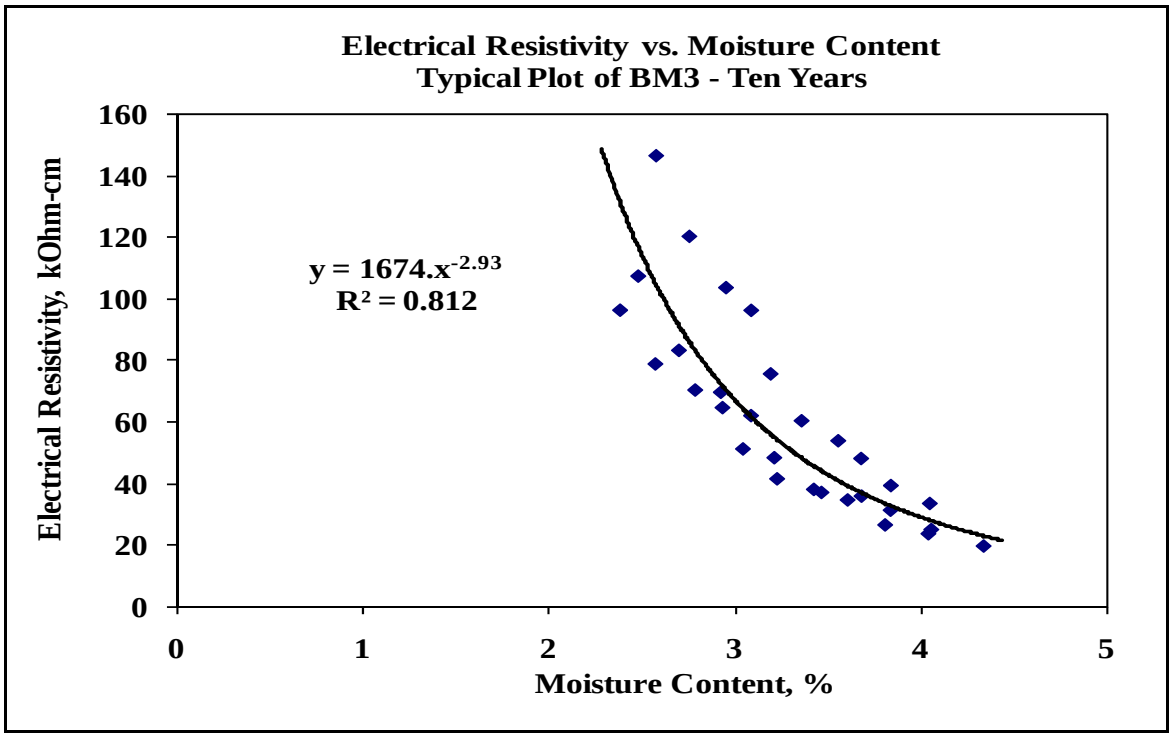


Figure 4.81. Typical variation of electrical resistivity with moisture content.

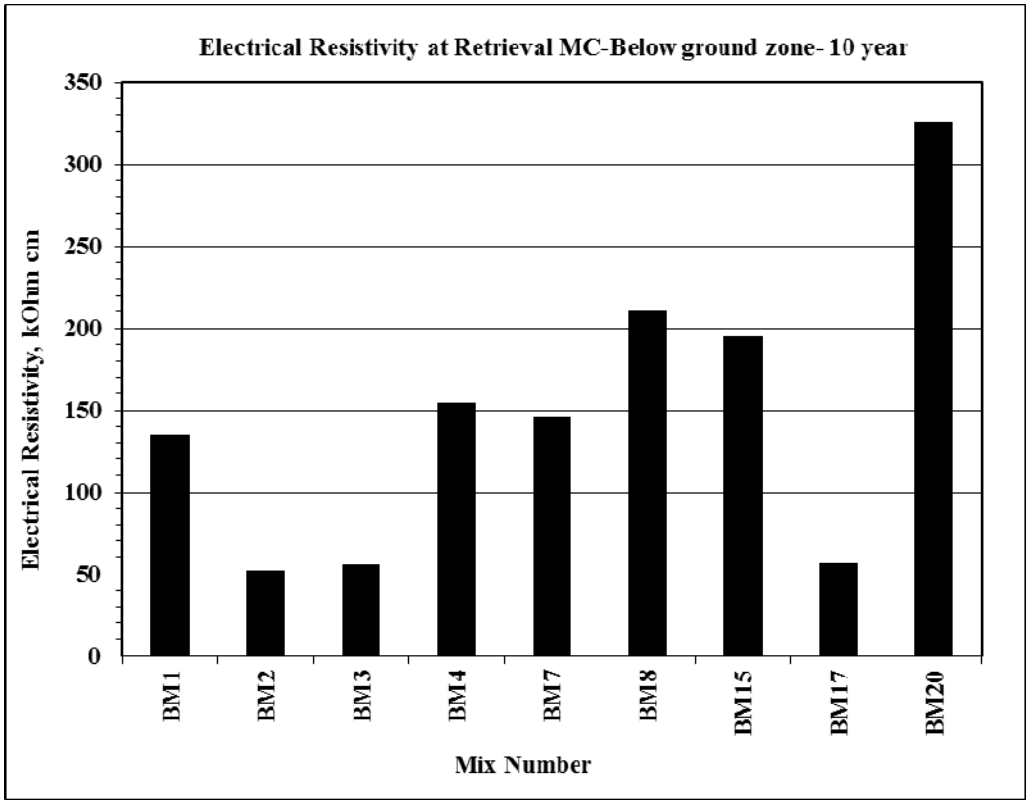


Figure 4.82. Electrical resistivity at the initial moisture content.

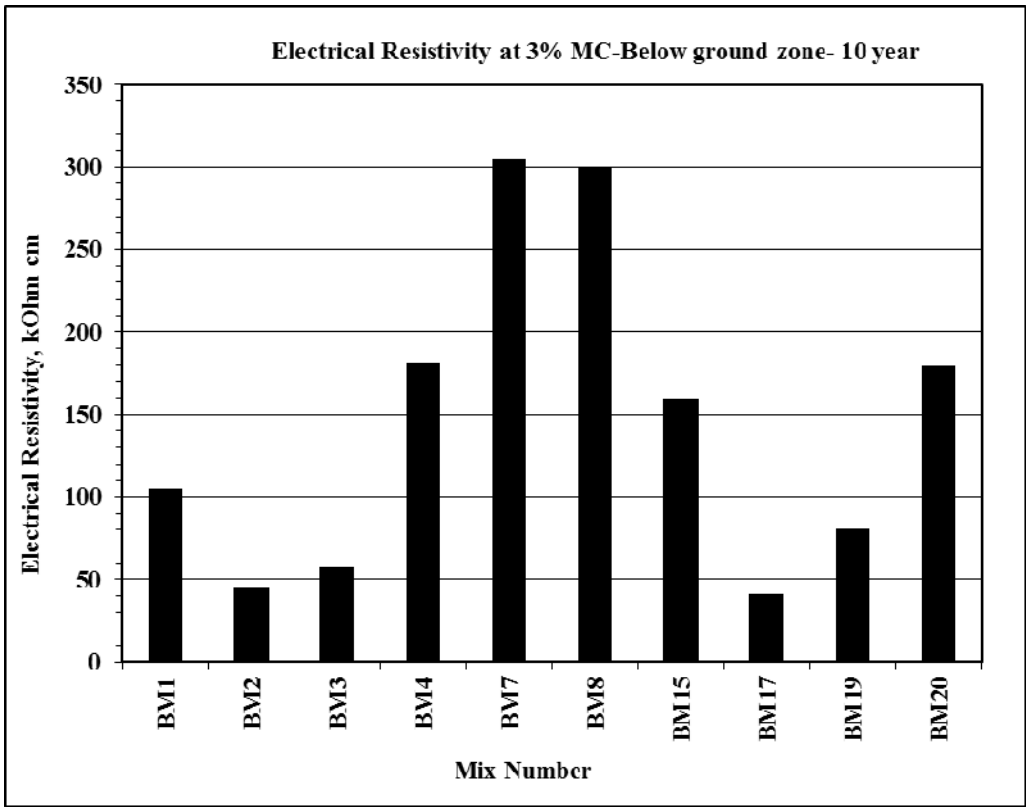


Figure 4.83. Electrical resistivity at 3% moisture content.

4.2.9 Water Absorption

The water absorption values are summarized in Table 4.74 and plotted in Figure 4.84.The water permeability of mixes M4 (low w/c ratio), M15 (10% superpozz) and M17 (30% FA) was better than that of other mixes. The water absorption in the other pozzolanic mixtures was more than 4%.

Table 4.74.Water absorption in the below ground portions.

Mix #	Water Absorption, %
BM1	3.69
BM2	4.21
BM3	4.22
BM4	3.75
BM7	4.53
BM8	4.17
BM15	3.57
BM17	3.73
BM20	5.07

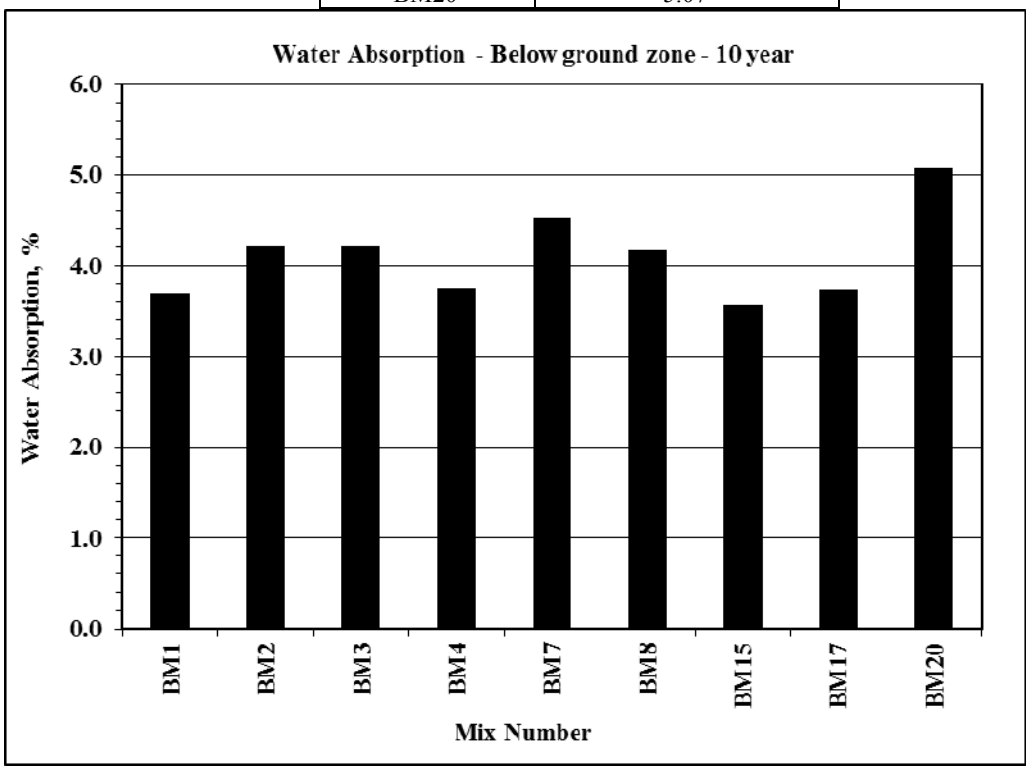


Figure 4.84.Water absorption in the concrete specimens placed in the below ground zone.

4.2.10 Compressive Strength

The compressive strength of cylindrical concrete specimens exposed in the below ground zone are provided in Table 4.75 and plotted in Figure 4.84. The compressive strength of Mix M1 (Type I cement) was more than that of mix M2 (Type V cement). The compressive strength of

Mixes M1, M3 (High cement content), M4 (Low w/c and w/SF) was more than 70 MPa. In the group of pozzolanic concretes (8% SF, 20% FA, 30% FA, 10% SuperPozz and 70% GGBFS), the compressive strength of mix M7 (8% SF) was the maximum followed by mixes M8 (20% FA), M15 (10% Superpozz) and M20 (70% GGBFS).

Table 4.75. Compressive strength of specimens exposed to below ground conditions.

Mix #	Compressive strength, MPa
BM1	70.77
BM2	57.43
BM3	73.84
BM4	73.33
BM7	68.92
BM8	63.71
BM15	65.68
BM17	60.06
BM20	53.36

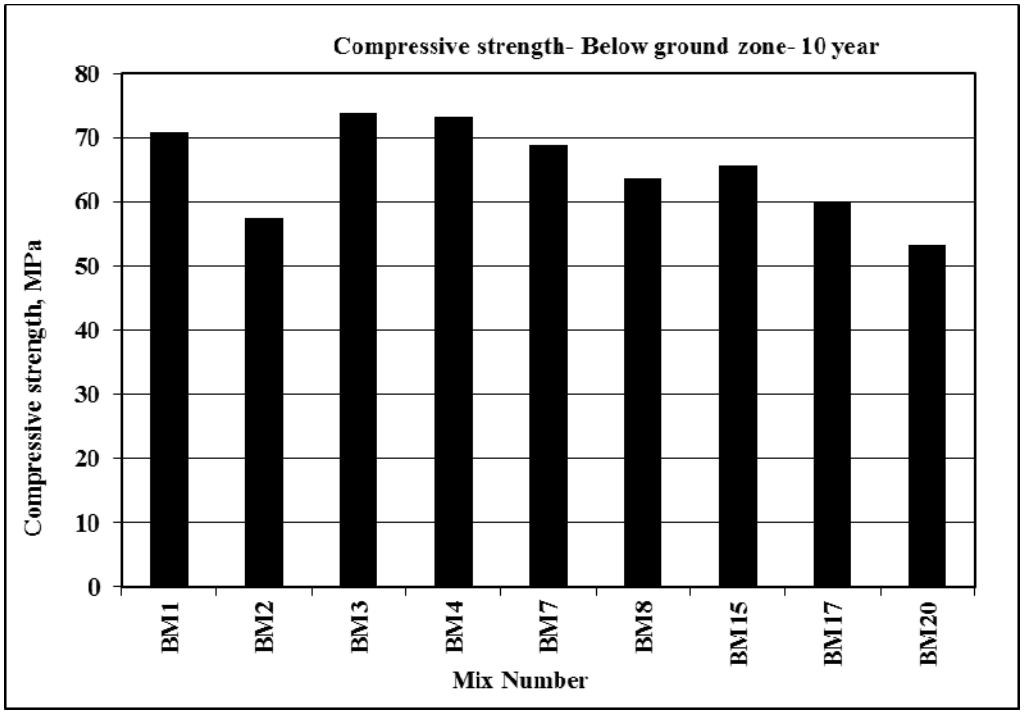


Figure 4.85.Compressive strength of concrete specimens placed in the below ground zone.

4.2.11. Depth of Carbonation

Carbonation was noted only in mix M1 (Type I cement) with a marginal depth of 1.5 mm. This behaviour of all the mixes is expected and it is attributed to the limited access to the atmosphere.

Table 4.76.Depth of carbonation in the specimens exposed to the below ground conditions.

Mix No.	Carbonation, mm
BM1	1.5
BM2	0.0
BM3	0.0
BM4	0.0
BM7	0.0
BM8	0.0
BM15	0.0
BM17	0.0
BM20	0.0

4.2.12 Morphology

Figures 4.86 and 4.87 show the SEM micrograph and EDS spectra for mixture BM1 (Type I cement concrete) exposed to soil (buried). The EDS spectra show the presence of calcium, silica, oxygen, iron, sulfur, sodium and aluminum. The EDS spectra shows 3.08% sulfur and 6.37% aluminum which indicates the presence of ettringite.

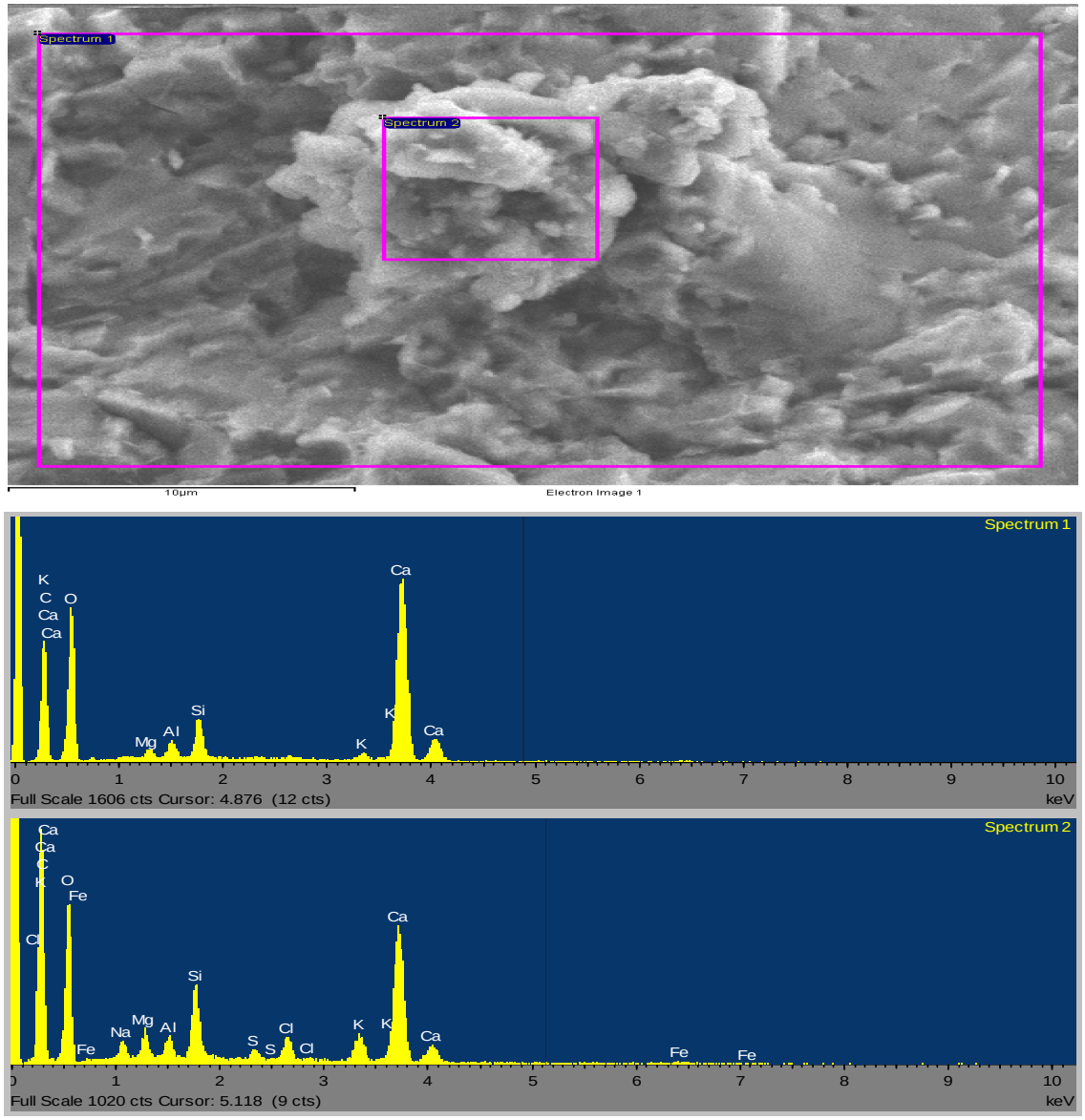
Figures 4.88 through 4.90 show the SEM micrograph and EDS spectra for mix BM2 (Type V cement concrete) exposed to soil (buried). The EDS spectra shows the presence of calcium, silica, oxygen, iron, sodium and aluminum. It should be noted that sulfur was not present in the sample indicating the absence of sulfate attack.

Figures 4.91 and 4.92 show the SEM micrographs and EDS spectra for BM7 (Type I cement concrete containing 8% silica fume) exposed to tidal zone. The spectra shows the presence of calcium, silica, oxygen, sodium, potassium, magnesium, aluminum and chloride. It should be noted that sulfur was not present in the sample indicating the absence of sulfate attack.

Figures 4.93 and 4.94 show the SEM micrographs and EDS spectra for BM17 (Type I cement concrete containing 30% fly ash) exposed to soil (buried). The spectra shows the presence of calcium, silica, oxygen, sodium, potassium, magnesium and aluminum. It should be noted that sulfur was not present in the sample indicating the absence of sulfate attack.

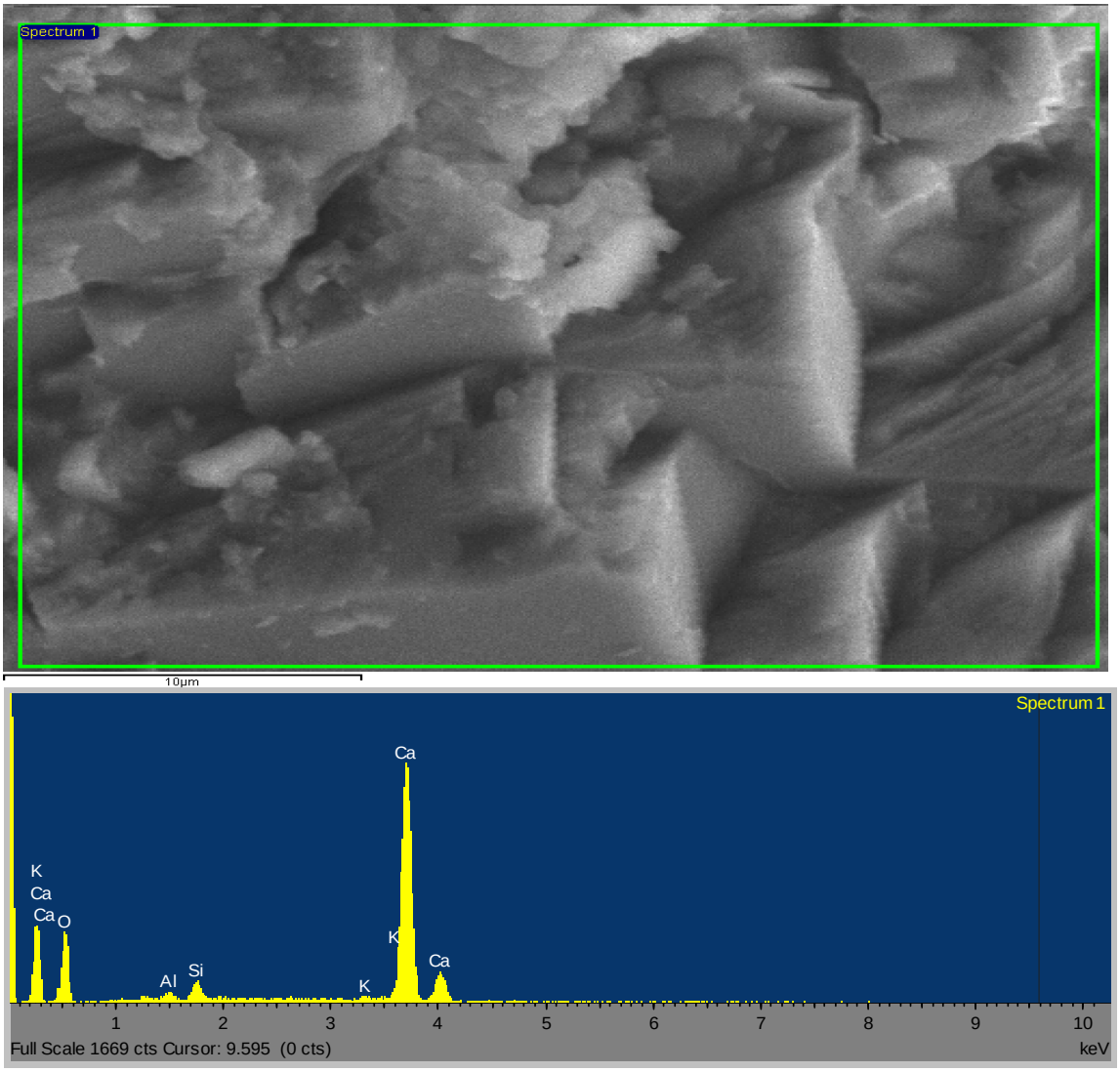
Figures 4.95 and 4.96 show the SEM micrographs and EDS spectra for BM20 (Type I cement concrete containing 70% blast furnace slag) exposed to tidal zone. The spectra shows the presence of calcium, silica, oxygen, sulfur and aluminum. The presence of sulfur and aluminum indicates the presence of ettringite and sulfate attack. Formation of ettringite can also be seen in the SEM micrograph.

The results of the SEM micrographs and EDS spectra of concrete samples exposed soil (buried) are summarized in Table 4.77. The results show that Type V cement concrete and Type I cement concrete containing silica fume and fly ash exposed to soil did not suffer sulfate attack. Therefore, these cements are recommended for buried structures.



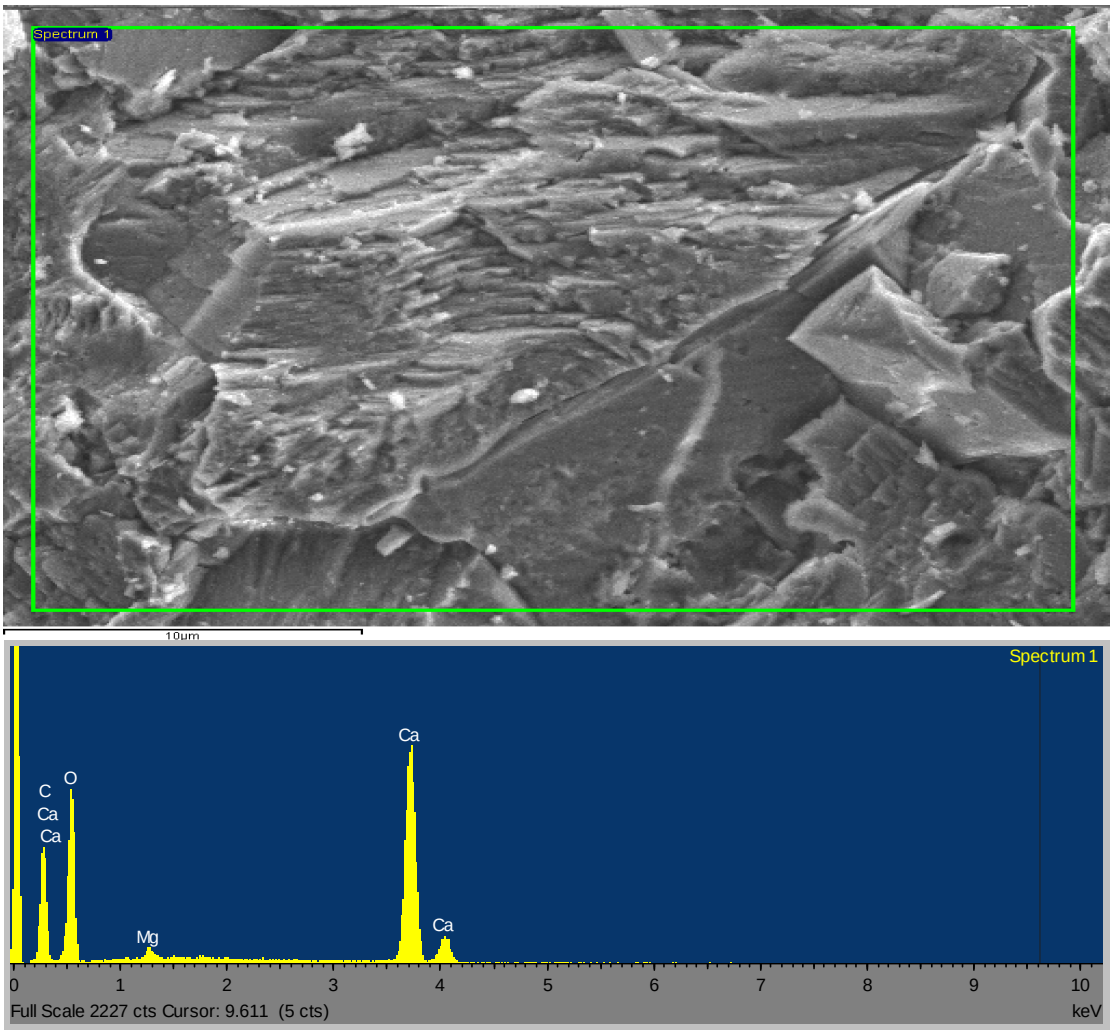
Element	O	Na	Mg	Al	Si	S	Cl	K	Ca	Fe	Total
Weight, %(Spectrum 1)	57.96	0.75	1.46	3.60			0.89	35.34			100.00
Weight, % (Spectrum 2)	53.66	2.21	1.65	6.37	1.14	3.08	4.13	24.62	1.19	1.9	100.00

Figure 4.86 SEM Micrograph and EDS Spectra for mix BM1 (Specimen 1).



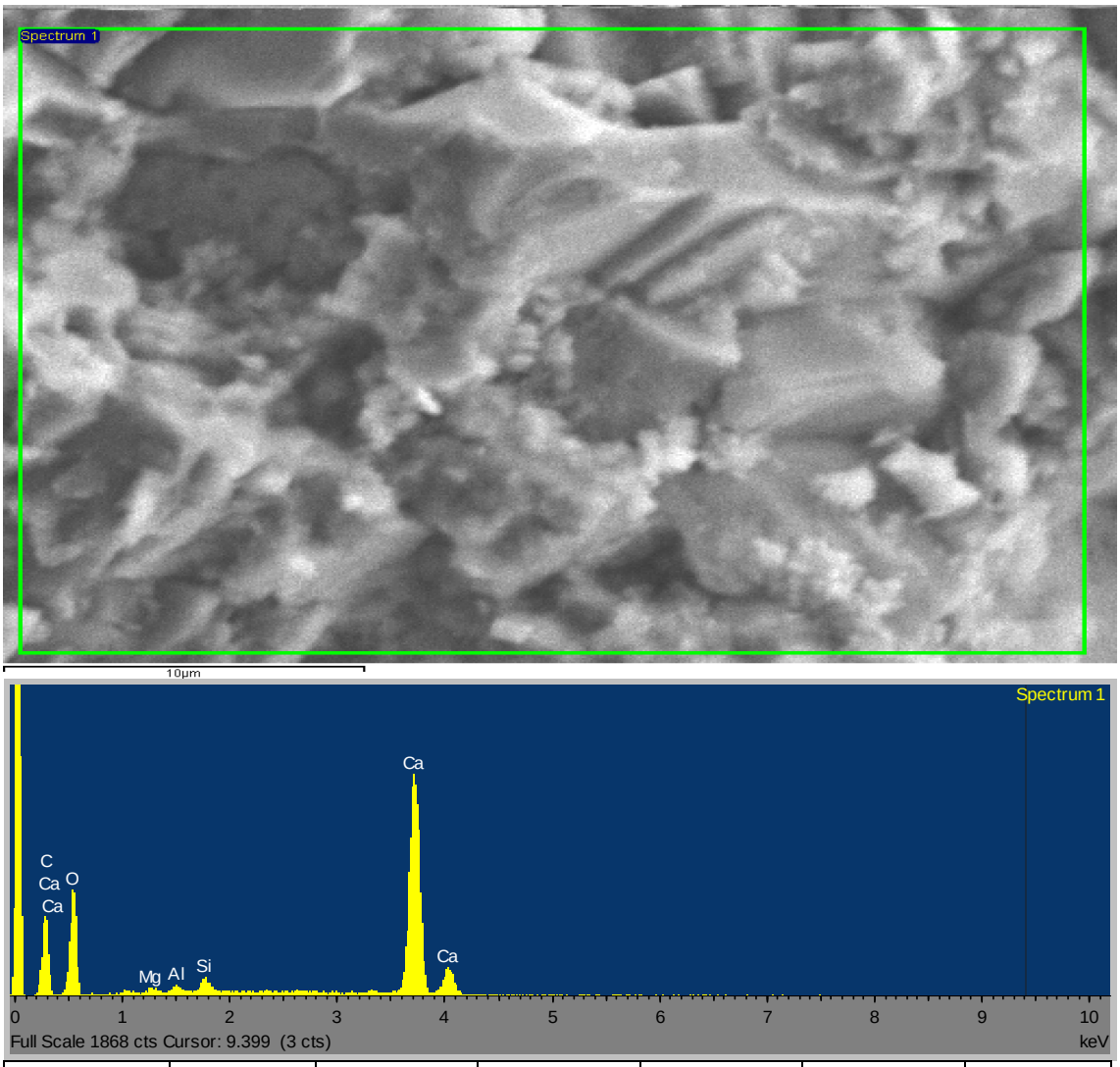
Element	O	Al	Si	K	Ca	Total
Weight, %	44.92	0.69	1.88	0.46	52.04	100.00

Figure 4.87. SEM Micrograph and EDS spectra for mix BM1 (Specimen 2).



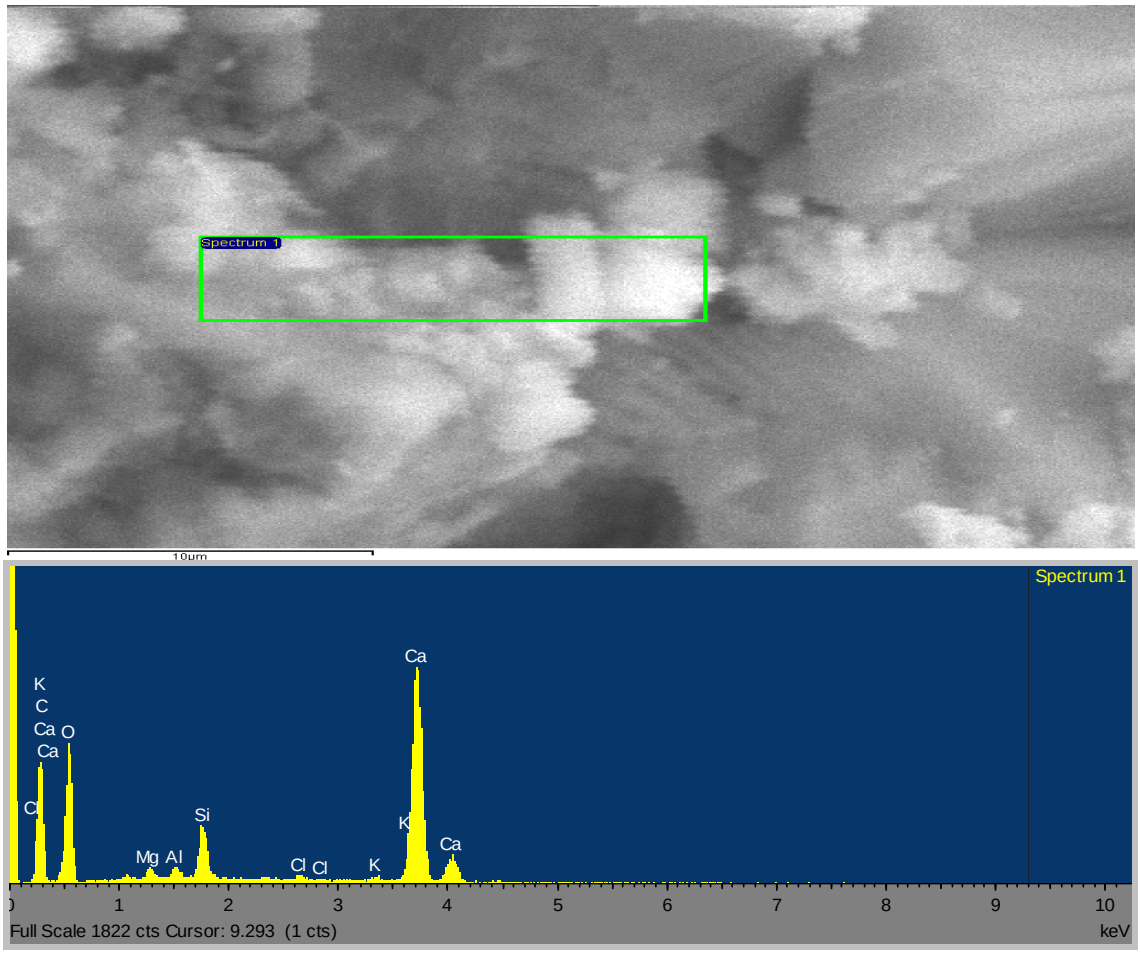
Element	O	Mg	Ca	Total
Weight, %	61.80	0.86	37.34	100.00

Figure 4.88. SEM micrograph and EDS of mix BM2 (Specimen 1).



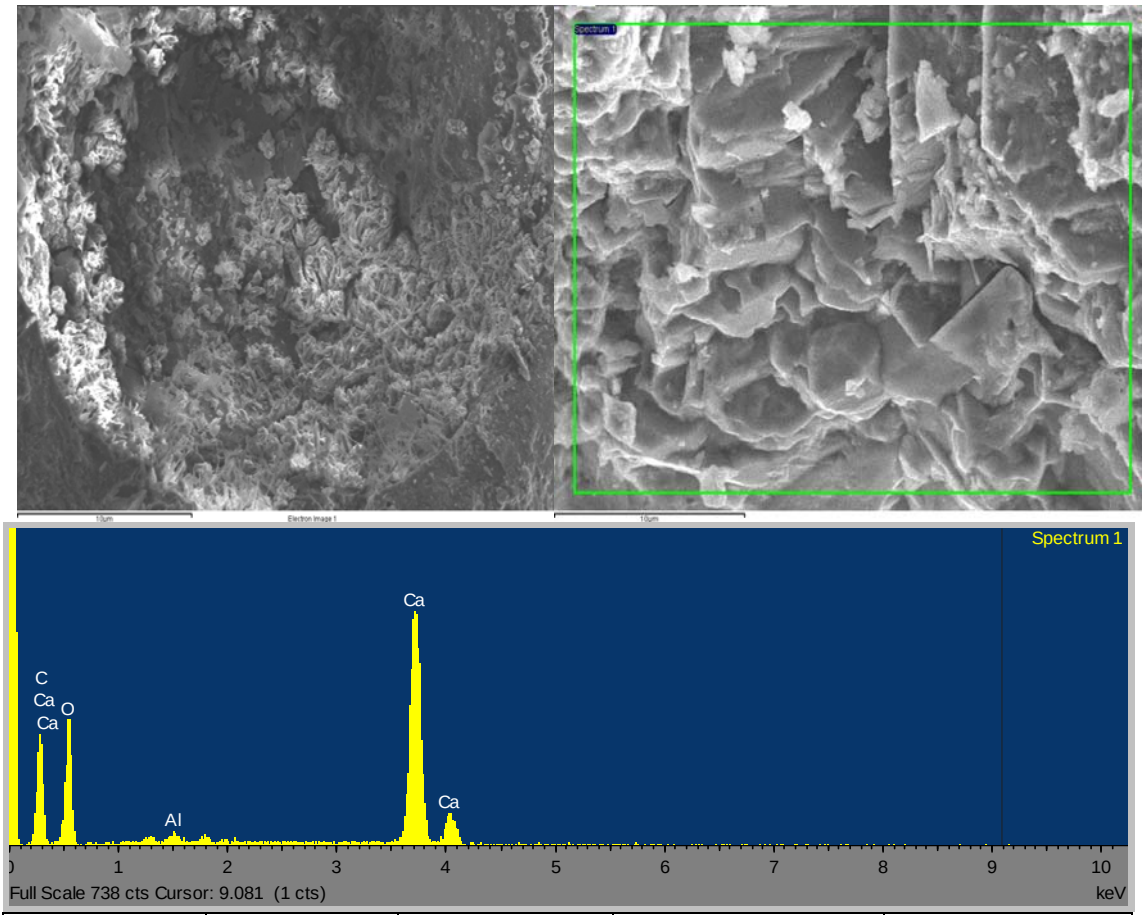
Element	O	Mg	Al	Si	Ca	Total
Weight, %	52.67	0.51	0.55	1.31	44.96	100.00

Figure 4.89. SEM micrograph and EDS spectra for mix BM2 (Specimen # 2).



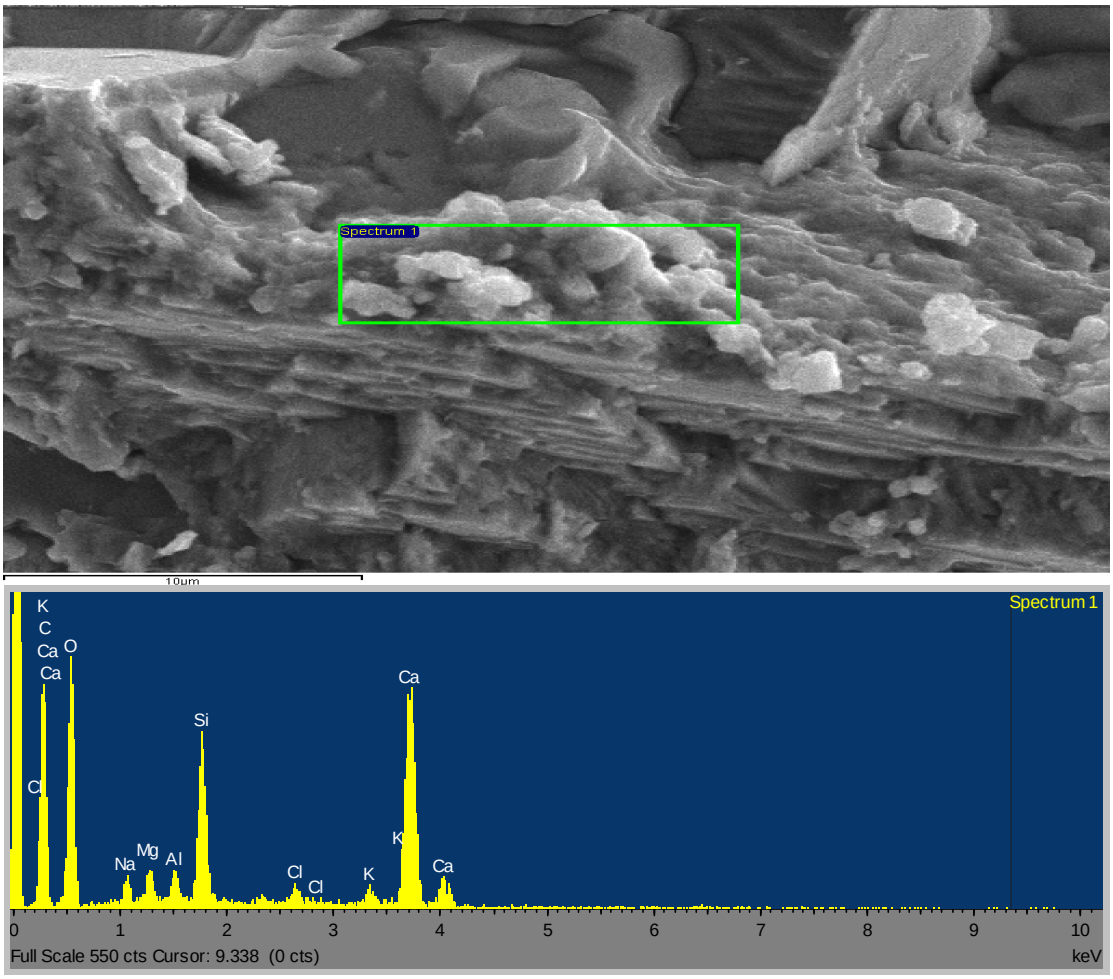
Element	O	Mg	Al	Si	Cl	K	Ca	Total
Weight, %	54.18	0.95	0.92	4.44	0.54	0.50	38.47	100.00

Figure 4.90. SEM micrograph and EDS spectra mix BM2 (Specimen # 3).



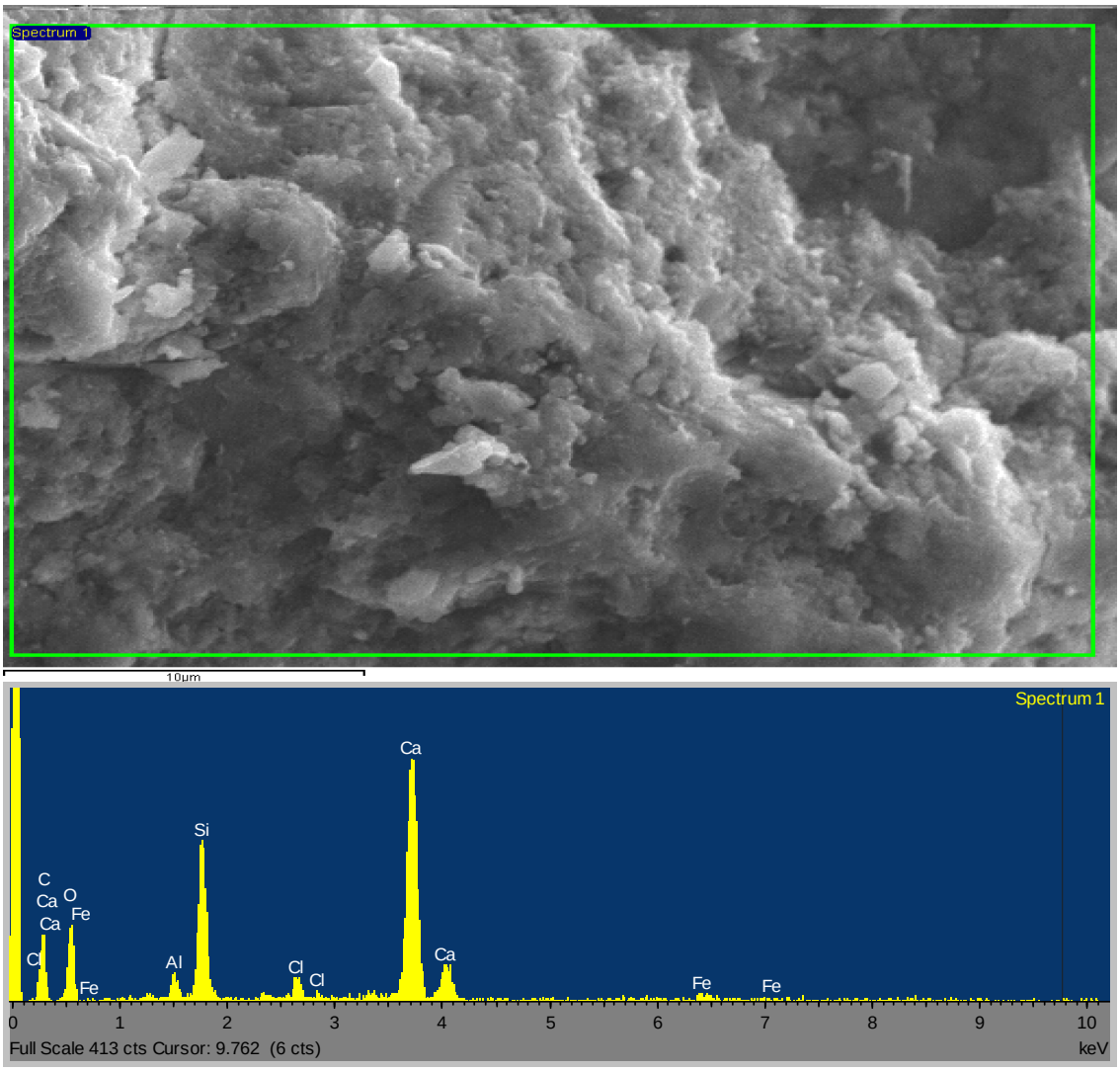
Element	O	Al	Ca	Total
Weight, %	55.26	0.64	44.10	100.00

Figure 4.91. SEM micrograph and EDS spectra for mix BM7 (Specimen 1).



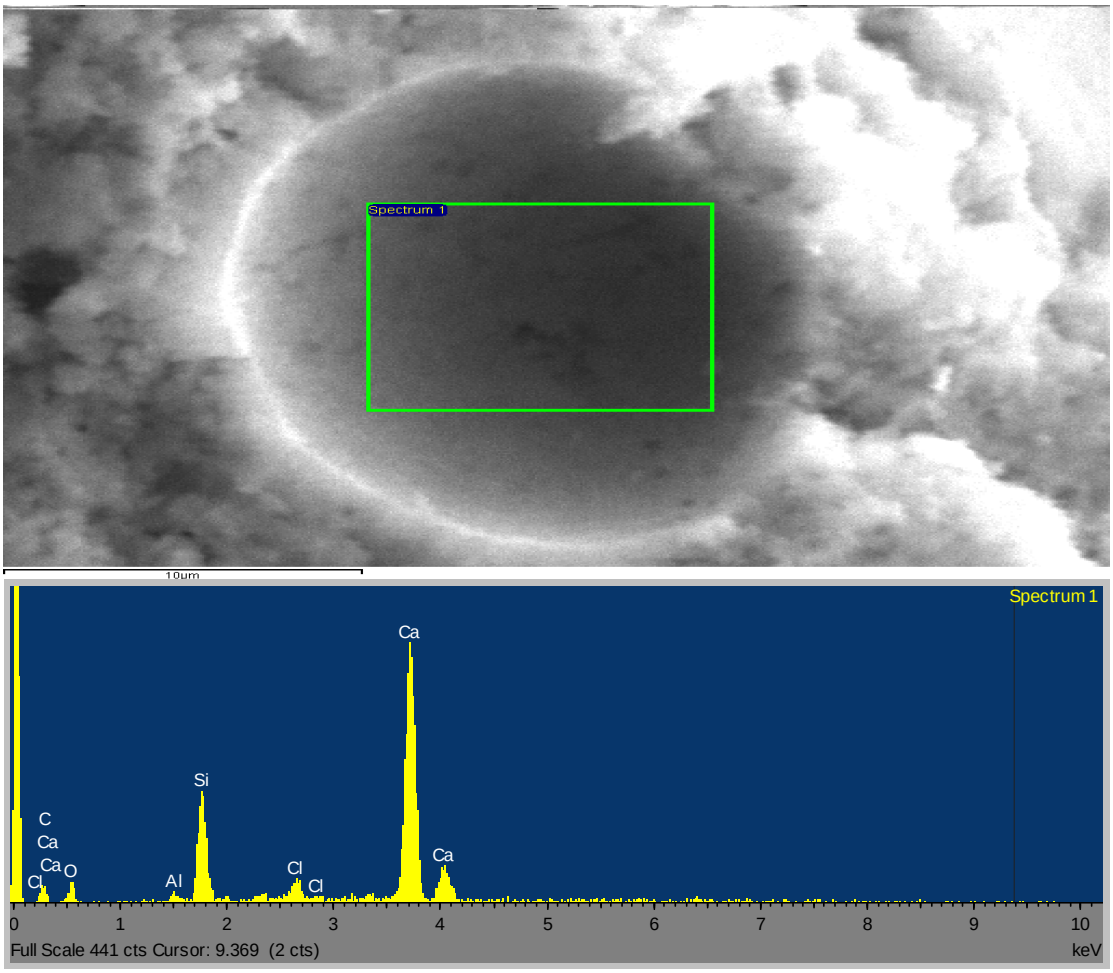
Element	O	Na	Mg	Al	Si	Cl	K	Ca	Total
Weight, %	55.43	2.14	1.73	1.49	9.08	1.26	1.41	27.47	100.00

Figure 4.92. SEM micrograph and EDS spectra mix BM7 (Specimen 2)



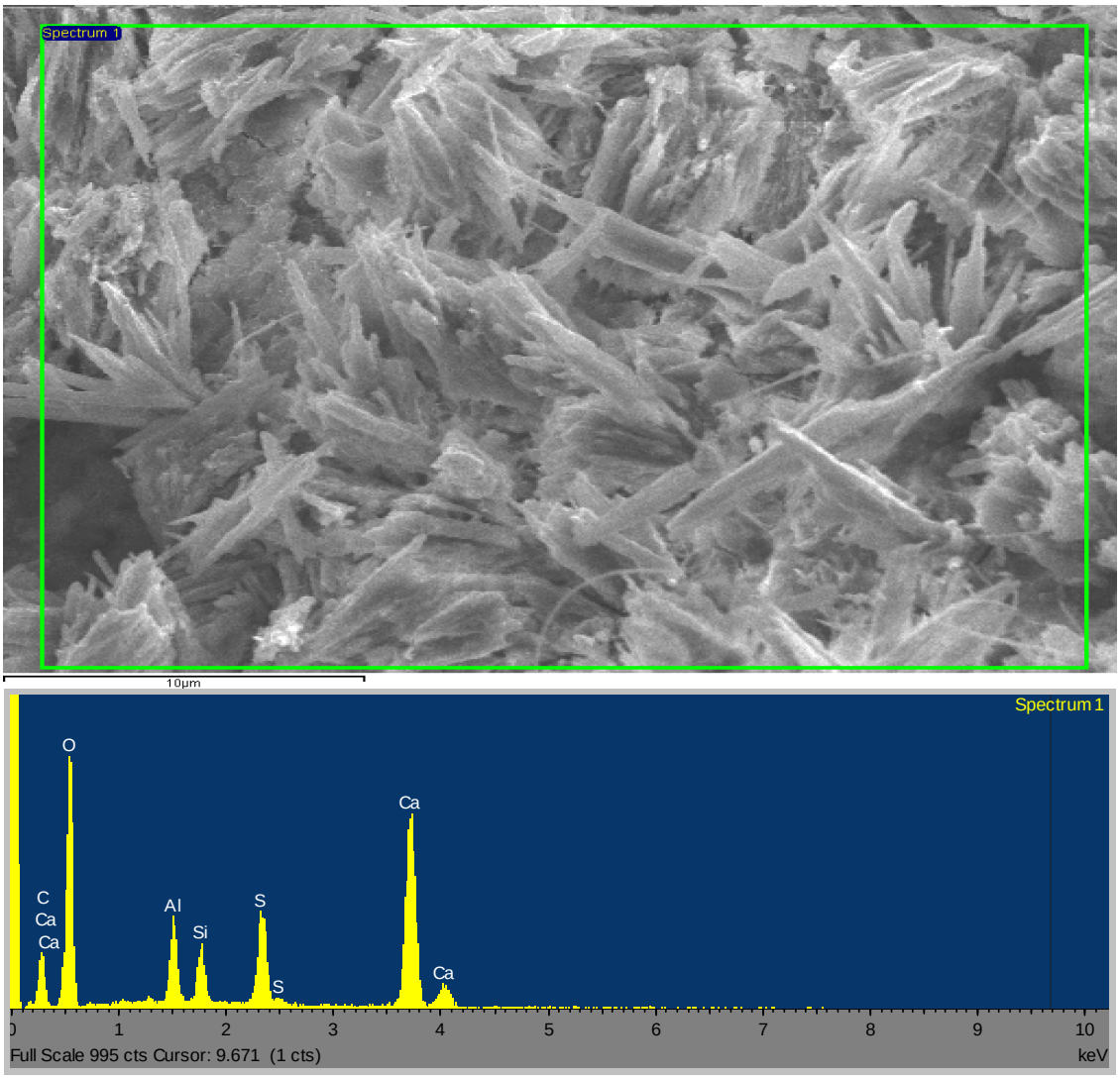
Element	O	Al	Si	Cl	Ca	Fe	Total
Weight, %	35.49	1.70	13.03	2.85	43.51	3.41	100.00

Figure 4.93. SEM micrograph and EDS spectra for mix BM17 (Specimen 1).



Element	O	Al	Si	Cl	Ca	Total
Weight, %	19.37	0.79	12.30	3.46	64.07	100.00

Figure 4.94. SEM micrograph and EDS spectra for mix BM17 (Specimen 2).



Element	O	Al	Si	S	Ca	Total
Weight, %	58.34	4.59	3.53	7.69	25.84	100.00

Figure 4.95. SEM micrograph and EDS spectra for mix BM20.

Table 4.77. Results of SEM micrographs and EDS spectra of concrete specimens exposed to soil (Buried).

Sample	Cement Type	Pozzolan	Sulfur Content (%)	Aluminum Content (%)	Sulfate Attack
BM1	I	None	3.08	6.37	Present
BM2	V	None	0	0.55-0.92	Absent
BM7	I	8% SF	0	0.64-1.49	Absent
BM17	I	30% FA	0	0.79-1.70	Absent
BM20	I	70% GGBFS	7.69	4.59	Present

SF: Silica fume; FA: Fly ash; GGBS: Ground granulated blast furnace slag

4.3 Above Ground Exposure

4.3.1 Visual Observations

CYLINDERS

Deterioration was not noted in cylindrical concrete specimens exposed to the above ground conditions. The color of concrete specimens did not change. A thin film of dust accumulated on all the specimens. Figure 4.96 shows a typical photograph of a specimens exposed for 10 years in the above ground zone.

CUBES

Deterioration was not noted in cubes specimen exposed the above ground conditions. No change in color was noted in any of the specimens. Figure 4.97 shows typical photograph of a specimen in this zone.

Figure 4.96. Cylindrical concrete specimens exposed to above ground conditions for 10 years.

Figure 4.97. Cube specimens exposed to above ground conditions for 10 years.

4.3.2 Chloride Concentration

The chloride concentration in the concrete mixtures exposed to the above ground conditions for 10 years is depicted in Figure 4.98. The chloride concentration at the rebar level after ten years of exposure in the above ground portion of partially buried columns is depicted in Figure 4.99as well as in Table 4.115. The results indicate that after 10 years the chloride concentration at the rebar level is between 0.009% and 0.066% by weight of concrete (i.e., 0.054% and 0.396% by weight of cement). The chloride concentration at the rebar level in four of the nine mixes exceeded the threshold chloride value of 0.025% by weight of concrete (i.e., 0.15% by weight cement). In general, the results indicate that the above ground exposure is less aggressive as compared with the below ground exposure. This is expected because the below ground specimens were directly exposed to ground water while the above ground specimens were not.

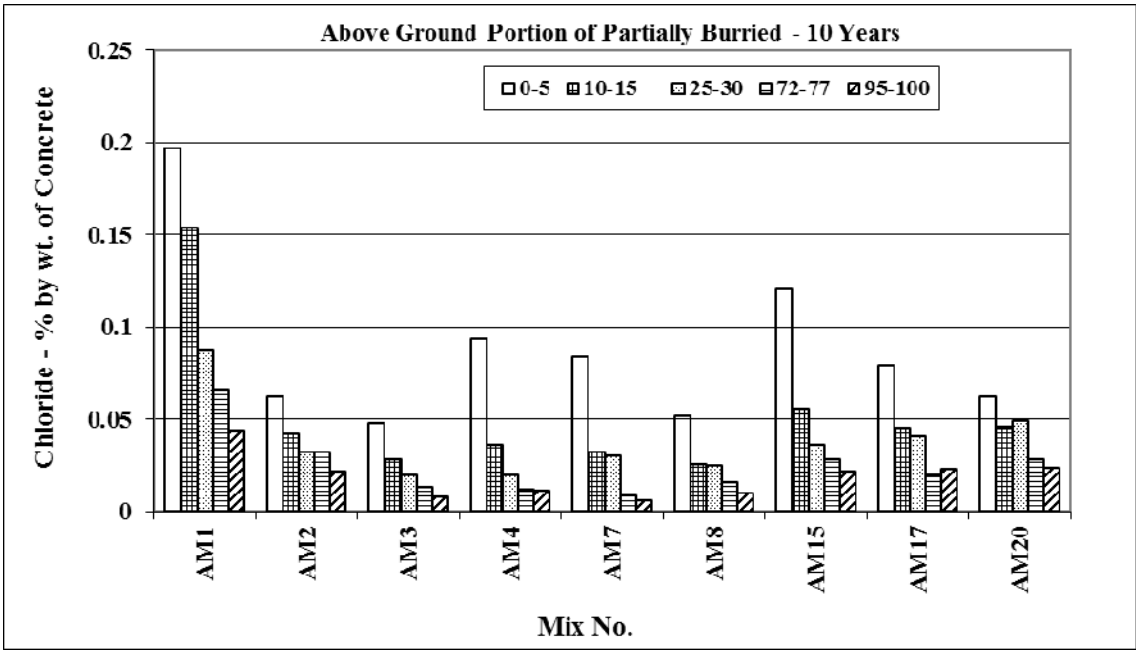


Figure 4.98. Chloride concentration profile in above ground portion of partially buried columns.

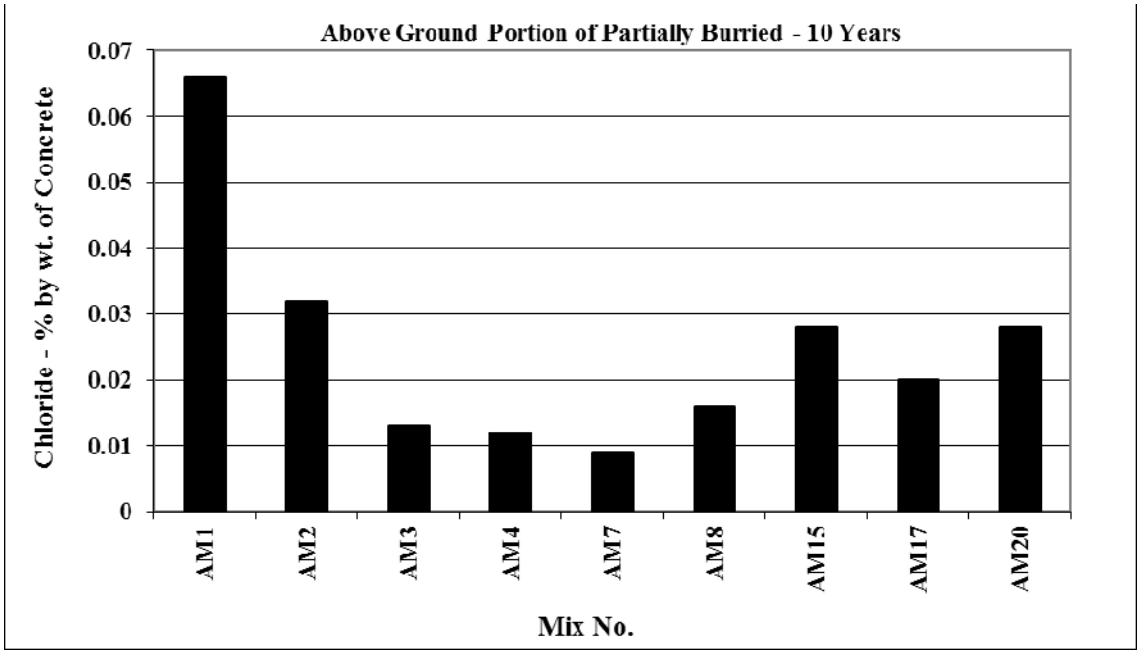


Figure 4.99. Chloride concentration at the rebar level in above ground portion of partially buried columns.

4.3.3 Sulfate Concentration

The sulfate concentration is summarized in Table 4.78and plotted in Figure 4.100.

The sulfate concentration at the rebar level (72-77 mm)in the pozzolanic concrete mixes ranged between 0.086% and 0.110%. These mixes exhibited better performance in terms of sulfate penetration compared to Mix M1 and M2. MixesM4, M15 and M17 showed better resistance to sulfate diffusion than other mixes.

Table 4.78. Sulfate concentration in the specimens exposed to atmospheric conditions.

Mix #	Sulfate ion concentration, % by weight of concrete				
	0-5 mm	10-15 mm	25-30 mm	72-77 mm	95-100 mm
AM1	0.189	0.142	0.110	0.095	0.086
AM2	0.189	0.157	0.133	0.110	0.094
AM3	0.165	0.110	0.102	0.086	0.086
AM4	0.145	0.109	0.095	0.086	0.074
AM7	0.172	0.144	0.122	0.095	0.086
AM8	0.165	0.157	0.110	0.110	0.082
AM15	0.142	0.112	0.105	0.099	0.076
AM17	0.140	0.129	0.111	0.086	0.074
AM20	0.162	0.122	0.108	0.102	0.096

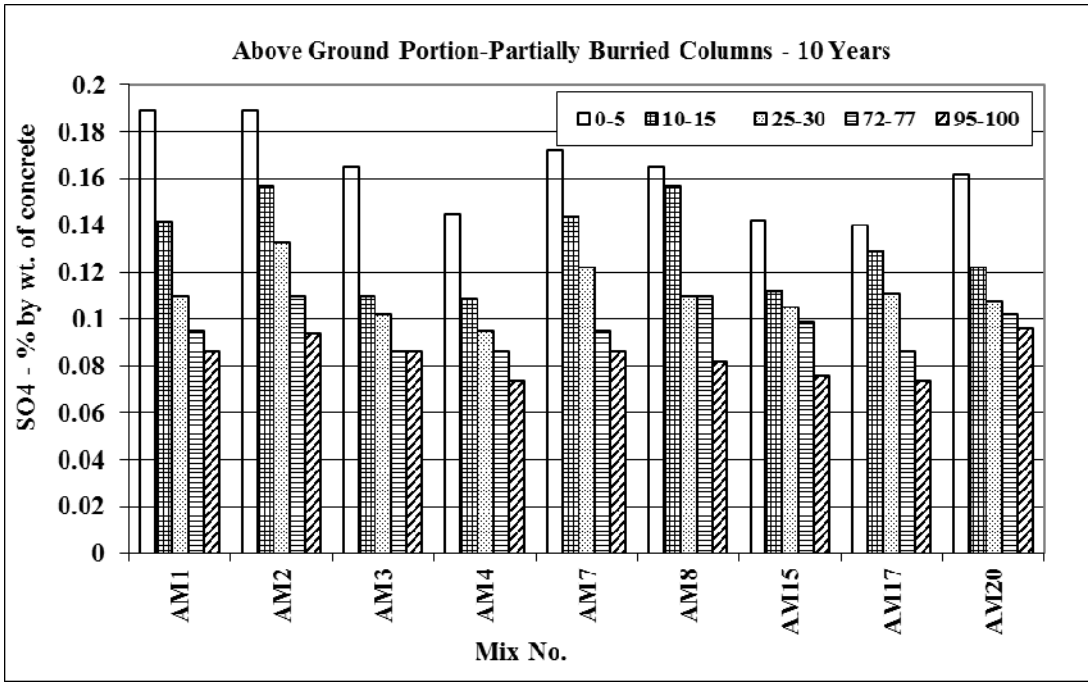


Figure 4.100.Sulfate concentration in the above ground portion of partially buried columns.

4.3.4 pH

The data, presented in Table 4.79 and Figure 4.101show that the pH values in the above ground portion of the exposed columns are very similar to those observed in the below ground portion. The pH values at the rebar level in all the mixes was more than 12, except in three

mixes with FA and GGBFS (AM8, AM17 and AM20) with the minimum pH value of 11.80. This marginal reduction in alkalinity can be attributed to the pozzolanic reaction.

Table 4.79. pH profile of the above ground portion of the partially buried columns.

Mix #	pH				
	Depth, mm				
	0-5 mm	10-15 mm	25-30 mm	72-77 mm	95-100 mm
AM1	11.38	11.92	12.16	12.31	12.35
AM2	12.08	12.38	12.38	12.38	12.40
AM3	12.00	12.3	12.32	12.36	12.40
AM4	12.03	12.26	12.33	12.36	12.36
AM7	11.56	11.68	11.98	12.08	12.18
AM8	11.08	11.68	11.72	11.92	12.02
AM15	11.78	12.24	12.26	12.32	12.36
AM16	11.56	12.19	12.23	12.24	12.24
AM17	11.38	11.56	11.92	11.98	12.03
AM20	11.08	11.28	11.34	11.78	12.04

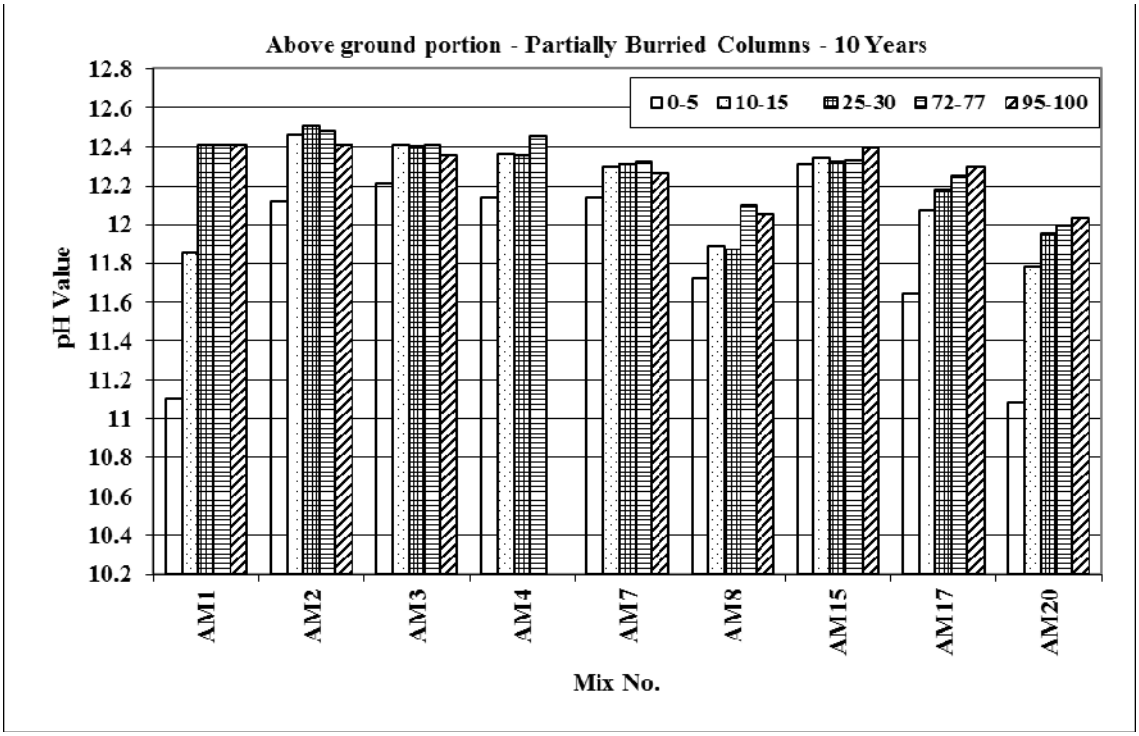


Figure 4.101. pH profile in above ground portion of partially buried of columns.

4.3.5 Water Permeability

The water permeability of above ground specimens are summarized in Table 4.80 and depicted in Figure 4.102. The water permeability in most of the specimens was more than 10 cm and some values were as high as 15 cm. The water permeability of mixes M17 (30% FA) and M20 (70% GGBFS) was 15 cm. The depth of water penetration in mixes M4 (High cement content,

low w/c ratio and 8% SF), M7 (8% SF) and M8 (20% FA) was between 11 and 12 cm while it was 13.6 cm in mix M15 (10% Super-Pozz). The depth of water penetration in mixes M1 (Type I cement) and M2 (Type V cement) was similar of about 10 cm.

Table 4.80. Depth of water penetration in the specimens placed in the atmospheric zone.

Mix #	Depth of water penetration, cm
M1	10.2
M2	10.4
M3	10.5
M4	11.2
M7	11.7
M8	11.8
M15	13.6
M17	15.0
M20	15.0

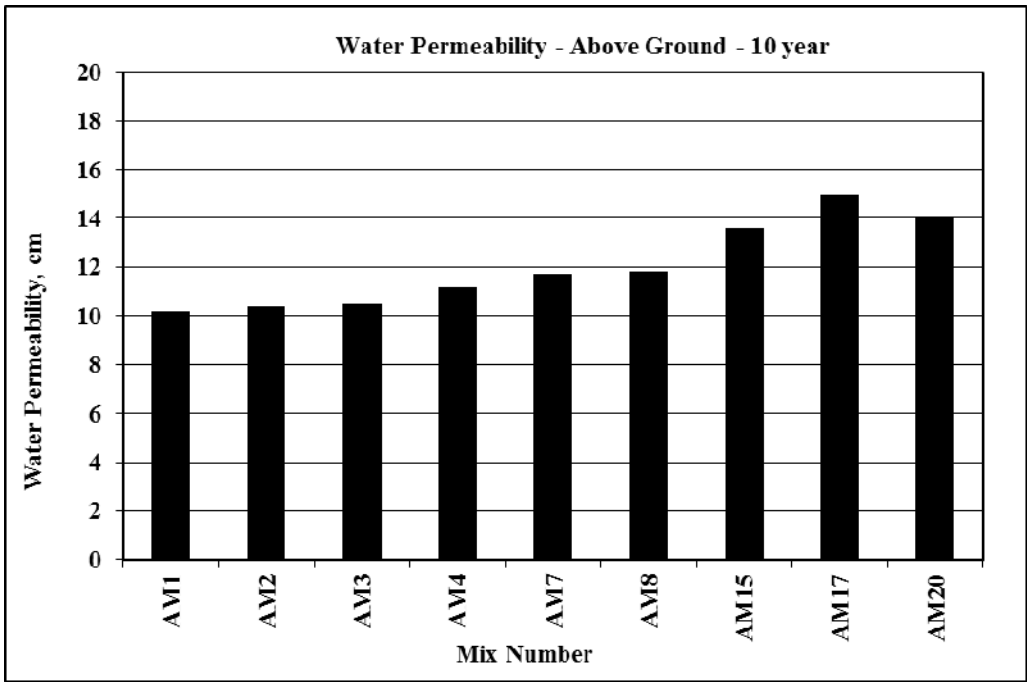


Figure 4.102. Depth of water penetration in the concrete specimens placed in the above ground zone.

4.3.6. Chloride Permeability

The chloride permeability is summarized in Table 4.81 and depicted in Figure 4.103.The chloride permeability in pozzolanic mixtures was in the very low and low range. The chloride permeability of mixes M1 (Type I cement), M2 (Type V cement), M3 (High cement content), was in the low range. The least chloride permeability was measured in mix M8, closely followed by that in mixes M17 and M20, indicating that the incorporation of fly ash decreased the chloride permeability.

Table 4.81. Chloride permeability of specimens placed in the above ground zone.

Mix #	Chloride permeability, Coulombs
AM1	1324
AM2	1977
AM3	1180
AM4	969
AM7	1047
AM8	787
AM15	1060
AM17	940
AM20	902

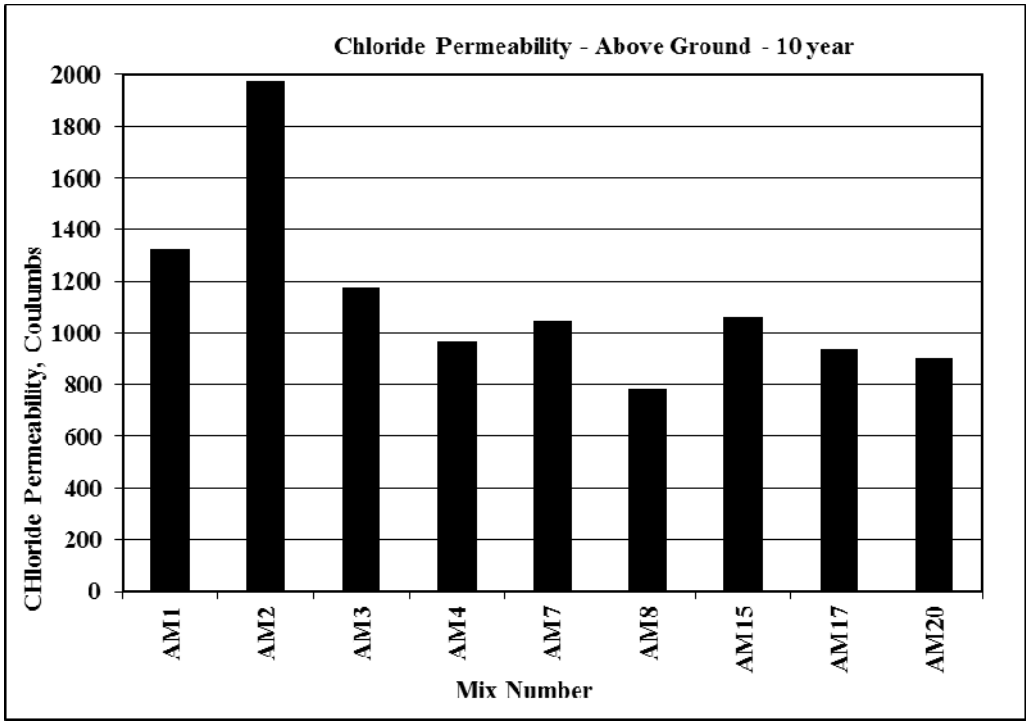


Figure 4.103. Chloride permeability of concrete specimens exposed to the atmospheric zone.

4.3.7. Electrical Resistivity

The electrical resistivity could not be measured in the specimens retrieved from the field due to the low moisture content (0.62 to 1.13%). Table 4.82summarizes these findings.

Table 4.83and Figure 4.105 show the electrical resistivity at 3% moisture content. The electrical resistivity of all the concrete mixes was within the range of 50 to 100 kOhm.cm with low risk of corrosion, with the exception of mixes M7 (8% SF) and M20 (70% GGBFS). These two mixes exhibited better performance compared to the other mixes with values more than 100 kOhm.cm with negligible risk of corrosion. Mixes M1 (Type I cement) and M2 (Type V cement) exhibited similar values.

Table 4.82. Electrical resistivity of specimens retrieved from the field.

Mix #	Moisture content, %	Electrical resistivity
AM1	0.97	High*
AM2	0.79	High*
AM3	1.03	High*
AM4	1.08	High*
AM7	1.12	High*
AM8	0.87	High*
AM15	1.04	High*
AM17	0.85	High*
AM20	0.91	High*

* No signal.

Table 4.83. Electrical resistivity 3% moisture content.

Mix #	Electrical resistivity, kOhm.com
AM1	67.3
AM2	76.3
AM3	83.6
AM4	95.8
AM7	127.0
AM8	76.7
AM15	82.3
AM17	71.1
AM20	142.7

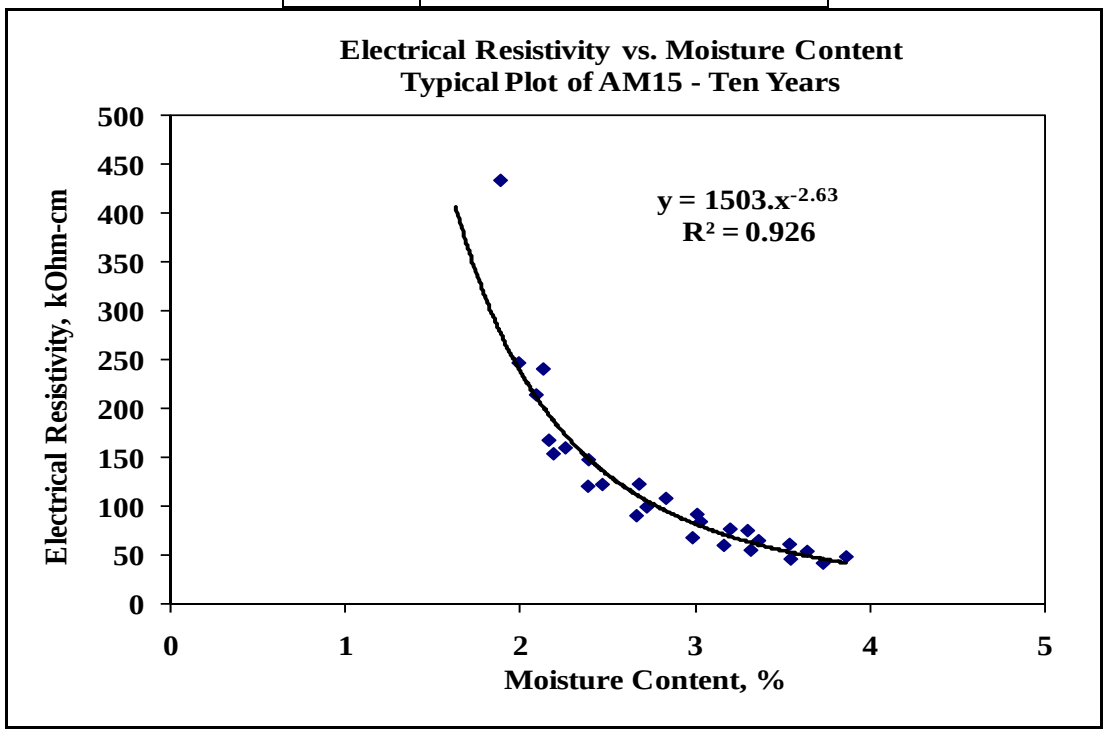


Figure 4.104.Typical variation of electrical resistivity with moisture content.

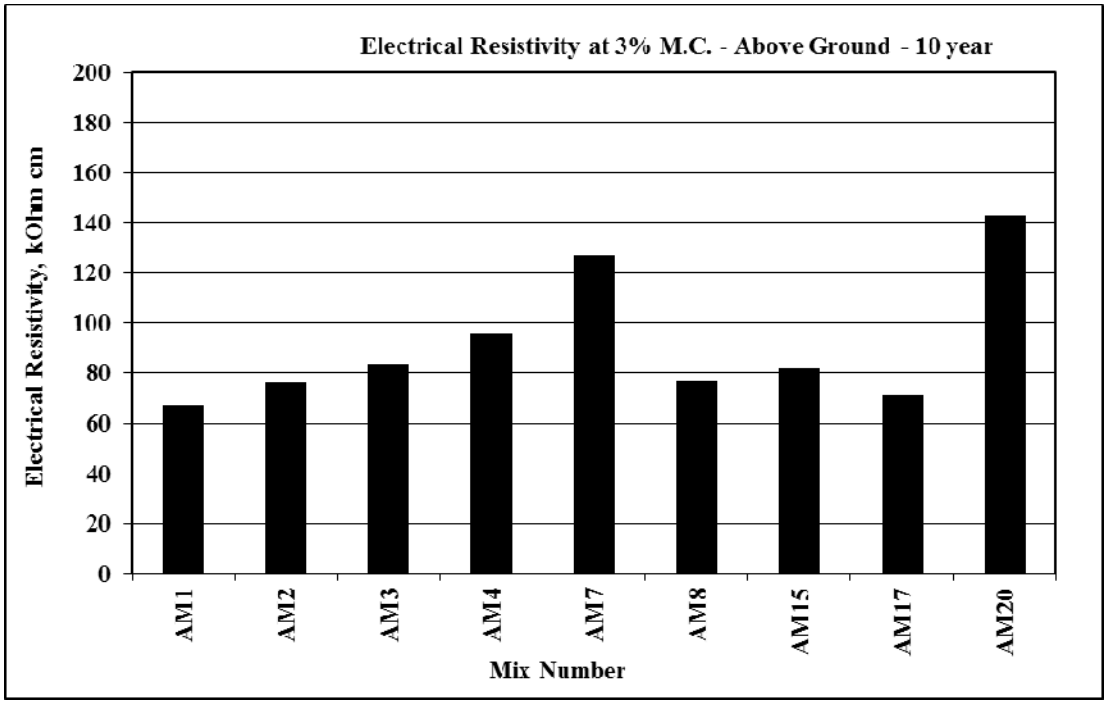


Figure 4.105. Electrical resistivity of concrete specimens at 3% moisture content.

4.3.8. Water Absorption

The water absorption is summarized in Table4.84and plotted in Figure 4.106. With the exception of mix M20, the water absorption values of all the mixes were within a narrow range of 3.9 and 4.39%. The water absorption of mix M1 (Type I cement) was almost similar to mix M2 (Type V cement) being 4.01% and 4.18%, respectively.

In the group of the pozzolanic concrete mixes, mix M4 (low w/c ratio), M8 (20% FA), and M15 (10% superpozz) exhibited lower water absorption than other mixes. The water absorption in the other pozzolanic mixtures was more than 4%.

Table 4.84. Water absorption in the specimens exposed to the atmospheric zone.

Mix #	Water Absorption, %
AM1	4.01
AM2	4.18
AM3	4.07
AM4	3.98
AM7	4.25
AM8	3.95
AM15	3.96
AM17	4.25
AM20	5.29

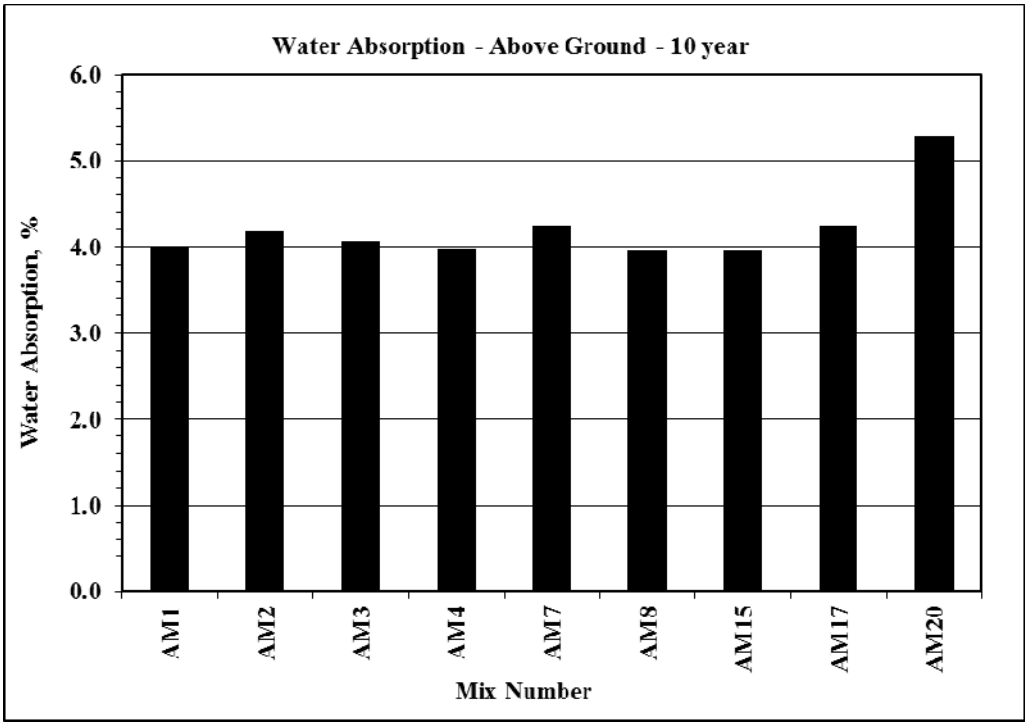


Figure 4.106. Water absorption in the concrete specimens placed in the above ground zone.

4.3.9 Compressive Strength

The compressive strength of specimens placed in the above ground zone is summarized Table 4.86 and depicted in Table 4.85 and Figure 4.107. The compressive strength of all the mixes was more than 40 MPa. In the group of pozzolanic concretes, the compressive strength of mixes M7, M8, M15 and M17 (8% SF, 20% FA, 30% FA and 10% Superpozz) was better than other mixes. The compressive strength of mix M20 with 70% GGBFS was the lowest in this group, being40 MPa.

Table 4.85. Compressive strength in the field exposed specimens after ten years exposure.

Mix #	Compressive strength, MPa
AM1	55.84
AM2	48.12
AM3	52.43
AM4	54.63
AM7	57.23
AM8	57.93
AM15	55.83
AM17	61.48
AM20	40.31

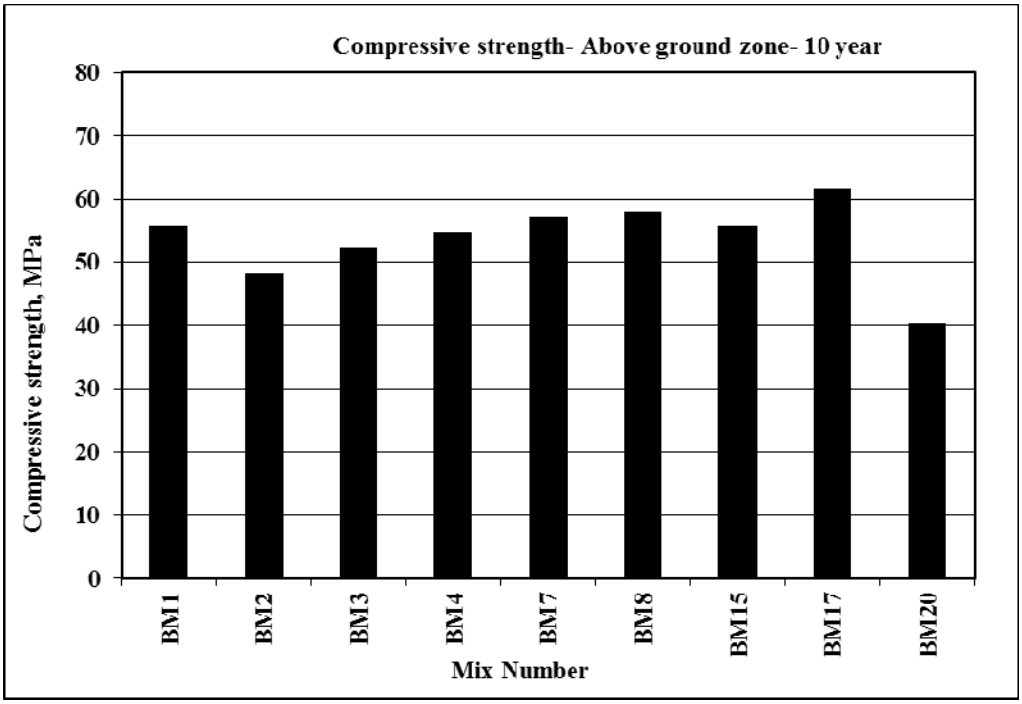


Figure 4.107. Compressive strength of concrete specimens placed in the above ground zone.

4.3.10. Depth of Carbonation

The depth of carbonation in above ground portions of partially buried columns is summarized in Table 4.86 and depicted in Figure 4.108. Carbonation was noted in only three concrete mixtures, namely M1 (type I cement), M3 (high cement content), and M8 (20% FA).

The depth of carbonation in this batch of specimens was more than that in the specimens placed in the tidal and below ground zones. This may be attributed to the continuous and direct exposure of these specimens to the atmospheric condition at the exposure site.

Table 4.86. Carbonation depth in the field exposed specimens after ten years exposure.

Mix #	Carbonation, mm
AM1	10.0
AM2	0.0
AM3	4.0
AM4	0.0
AM7	0.0
AM8	5.0
AM15	0.0
AM17	0.0
AM20	0.0

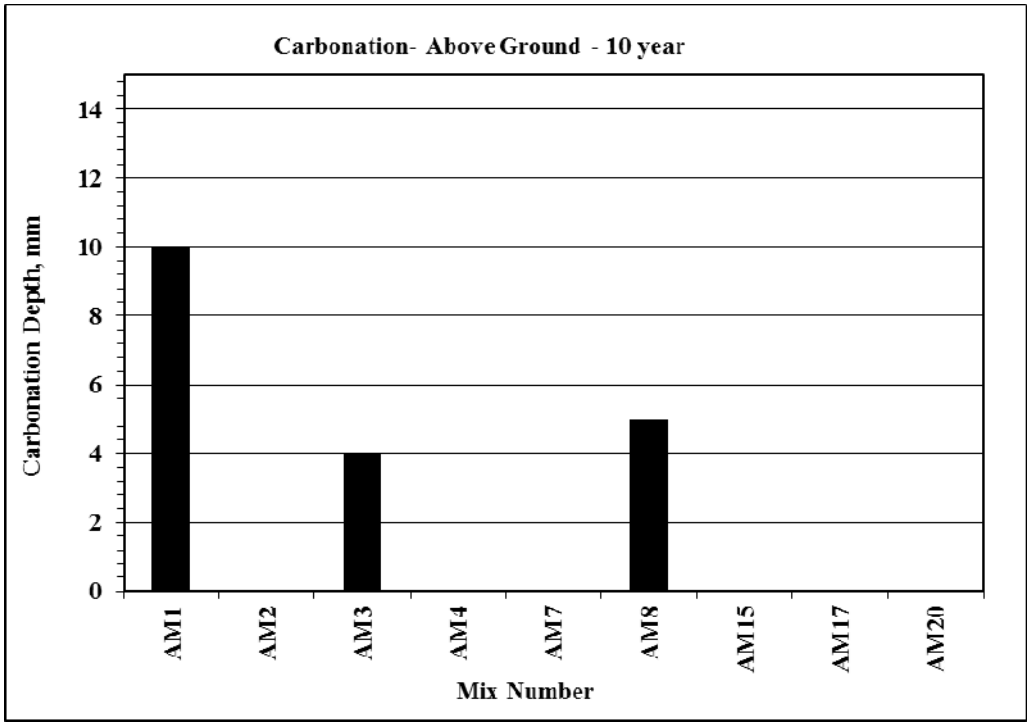


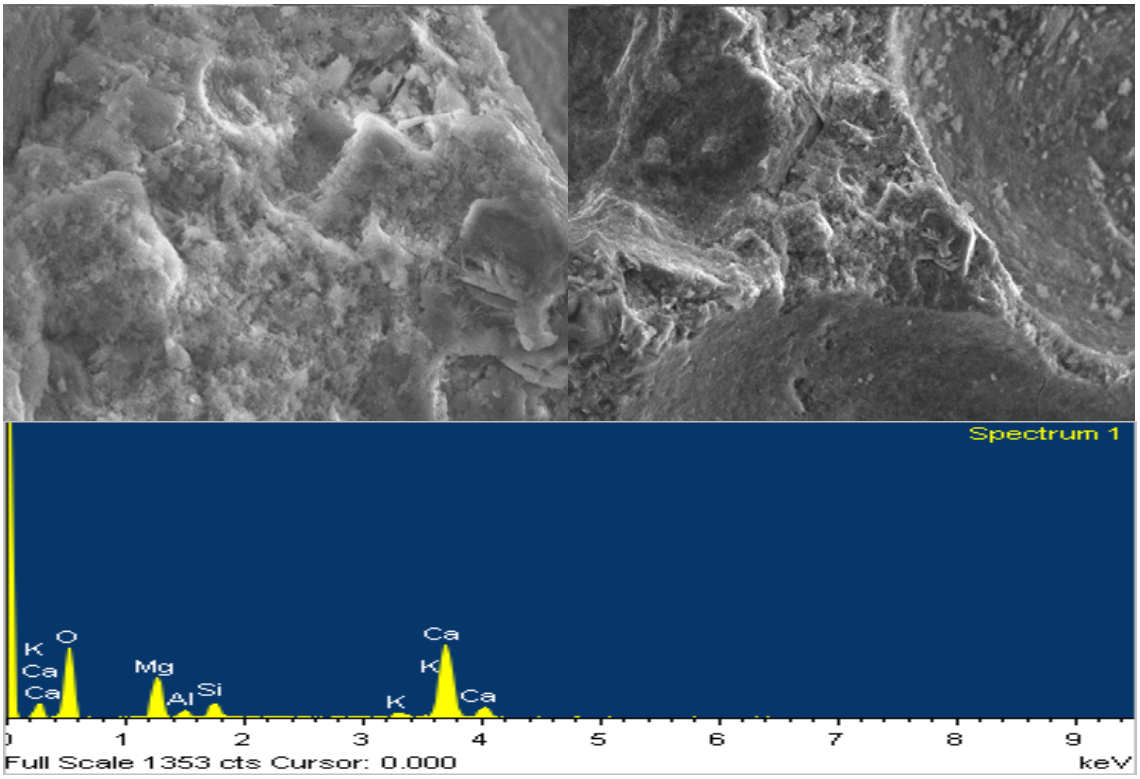
Figure 4.108. Depth of carbonation in the concrete specimens placed in the above ground zone.

4.3.11. Morphology

Figures 4.109 and 4.110 show the SEM micrograph and EDS spectra for mix AM1 (Type I cement concrete) exposed to the above ground conditions. The EDS spectra show the presence of calcium, silica, oxygen, iron, sulfur, aluminum, magnesium and chloride. Figure 4.2.12.11 shows 0.92% sulfur and 1.18% aluminum which indicate the presence of ettringite formed due to sulfate attack.

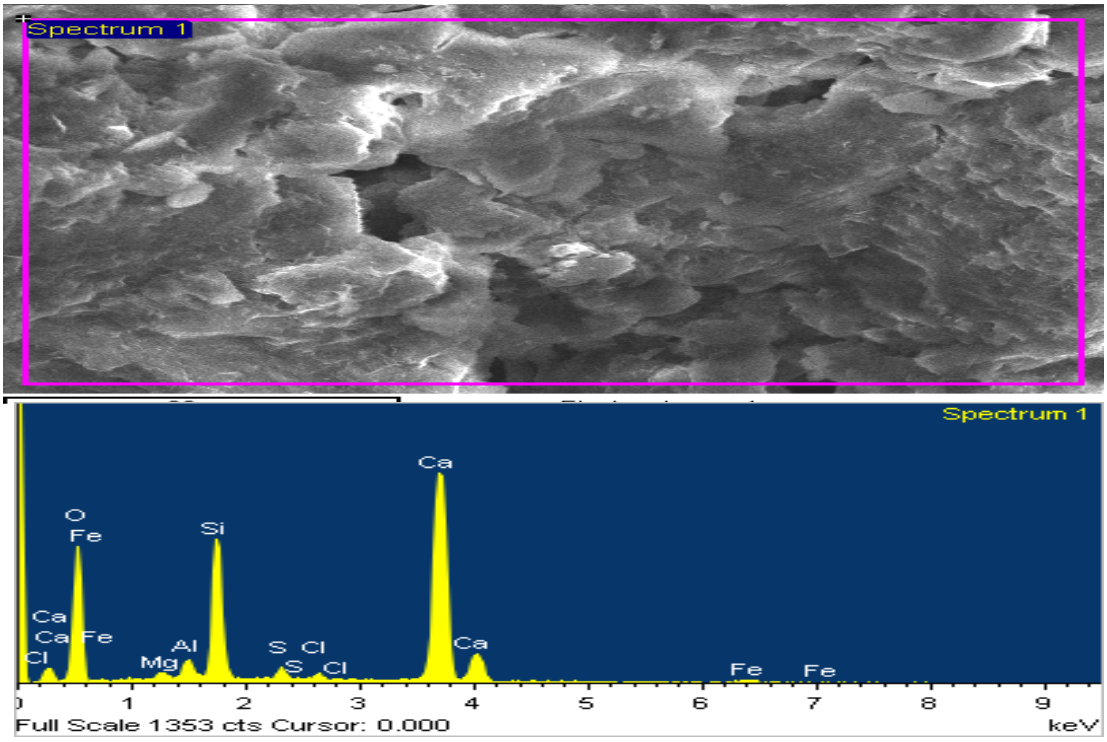
Figures 4.111 through 4.112 show the SEM micrograph and EDS spectra for mix AM2 (Type V cement concrete) exposed to above ground conditions. The spectra show the presence of calcium, silica, oxygen, iron, potassium, sulfur, magnesium, aluminum and chloride.

The results of the SEM micrographs and EDS spectra of concrete samples exposed atmosphere (above ground) are summarized in Table 4.85.



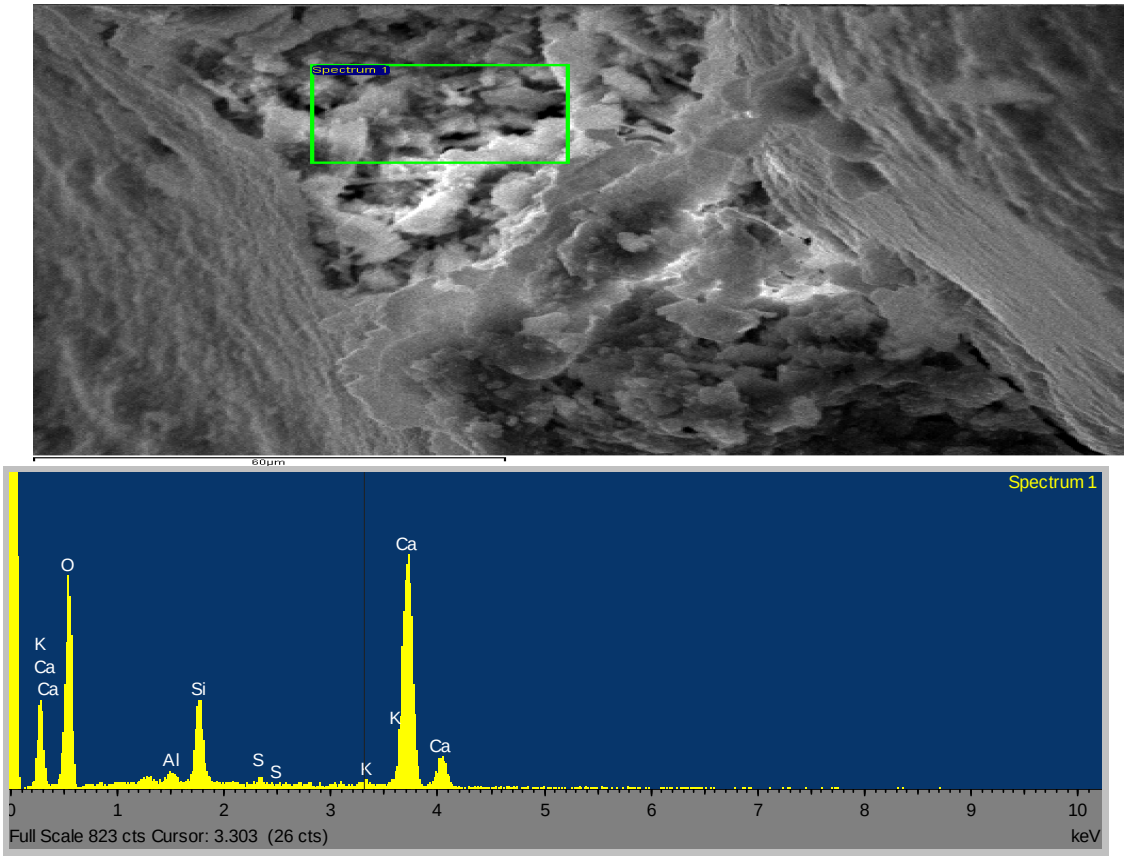
Element	O	Mg	Al	Si	S	Cl	Ca	Fe	Total
Weight, %	59.62	0.51	1.18	10.16	0.92	0.54	26.25	0.81	100.00

Figure 4.109. SEM micrograph and EDS Spectra for mix AM1 (Specimen 1).



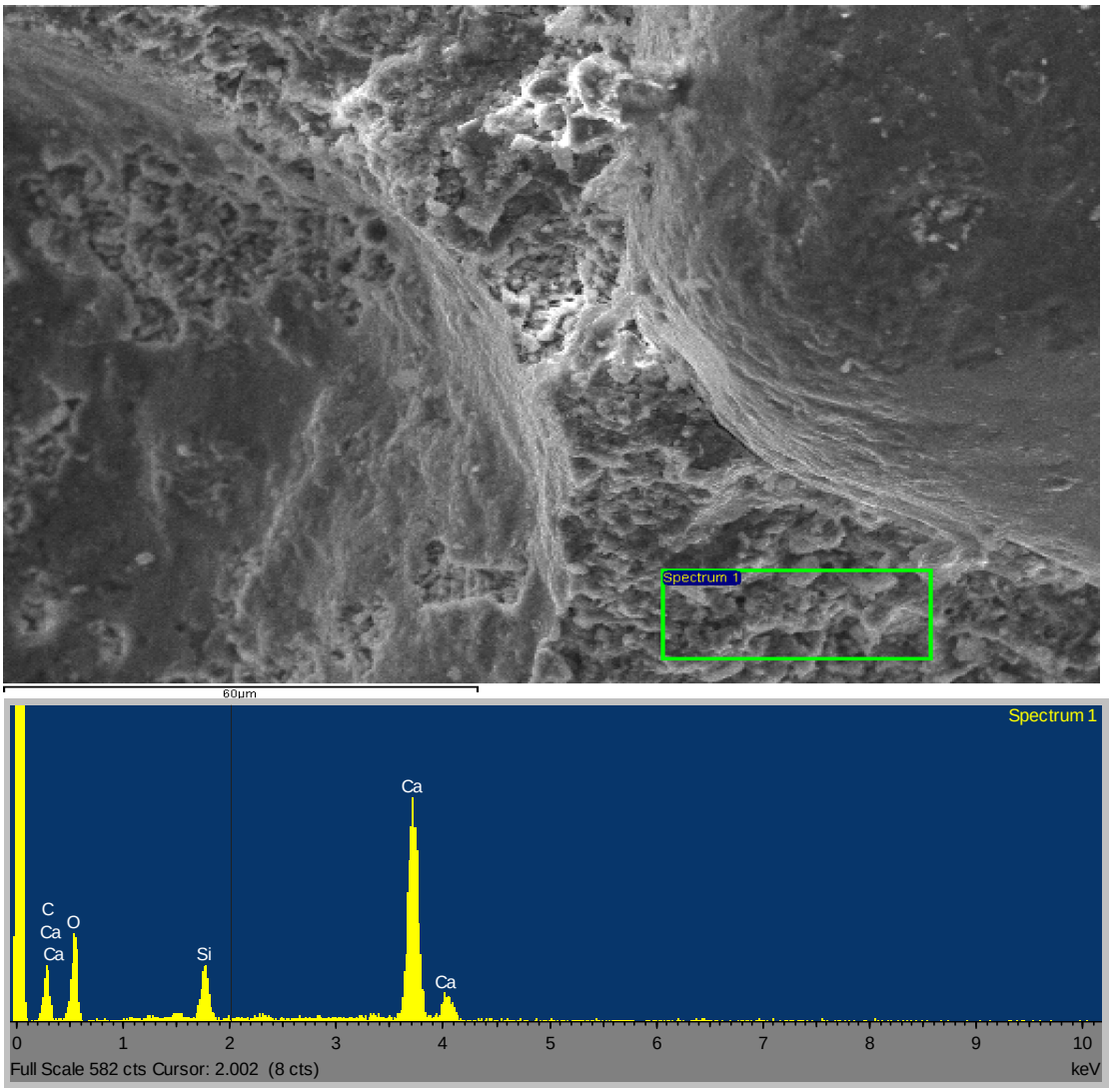
Spectrum	O	Mg	Al	Si	K	Ca	Total
Spectrum 1	63.91	9.36	1.42	2.86	1.11	21.34	100.00

Figure 4.110. SEM micrograph and EDS spectra for specimen AM1 (Specimen 2).



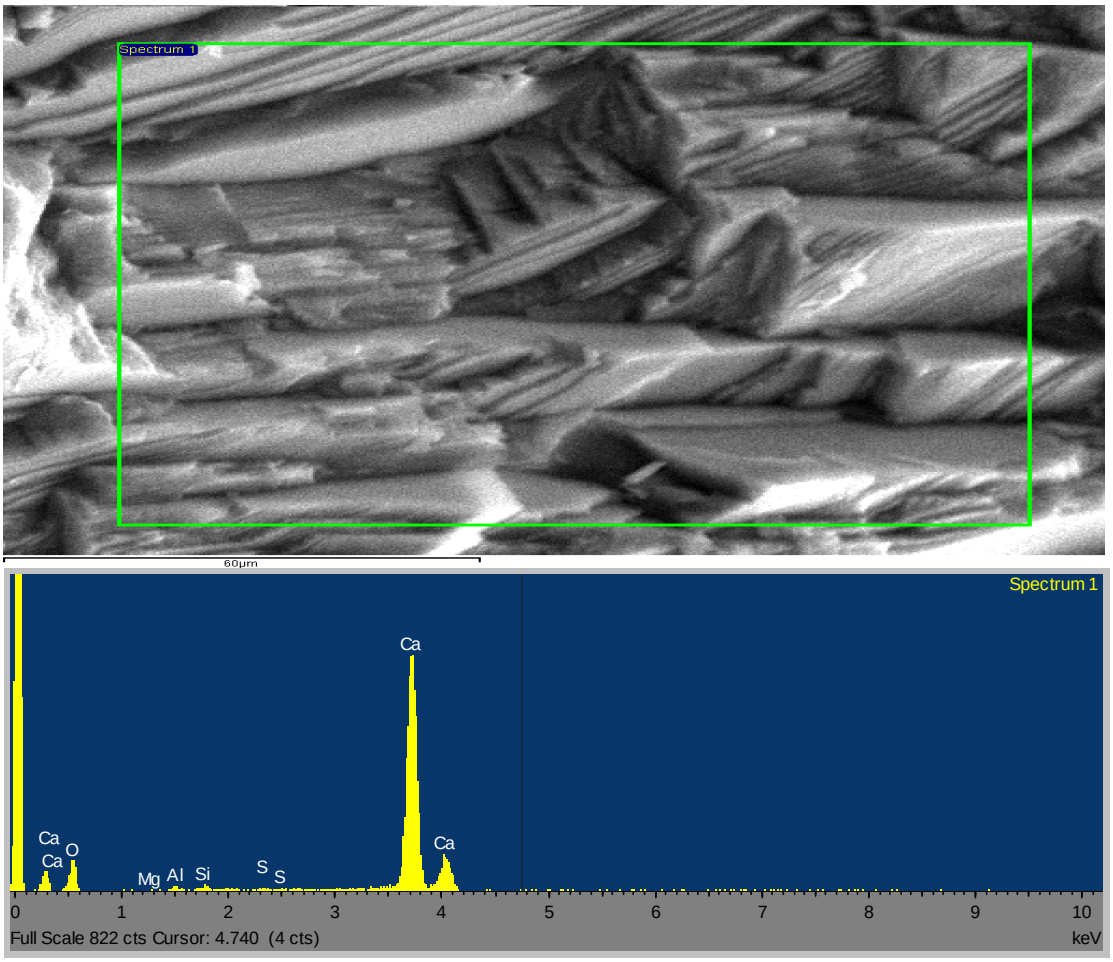
Element	O	Al	Si	S	K	Ca	Total
Weight %	59.24	0.64	5.59	0.48	0.43	33.63	100.00

Figure 4.111. SEM micrograph and EDS spectra for specimen AM2 (Specimen 1).



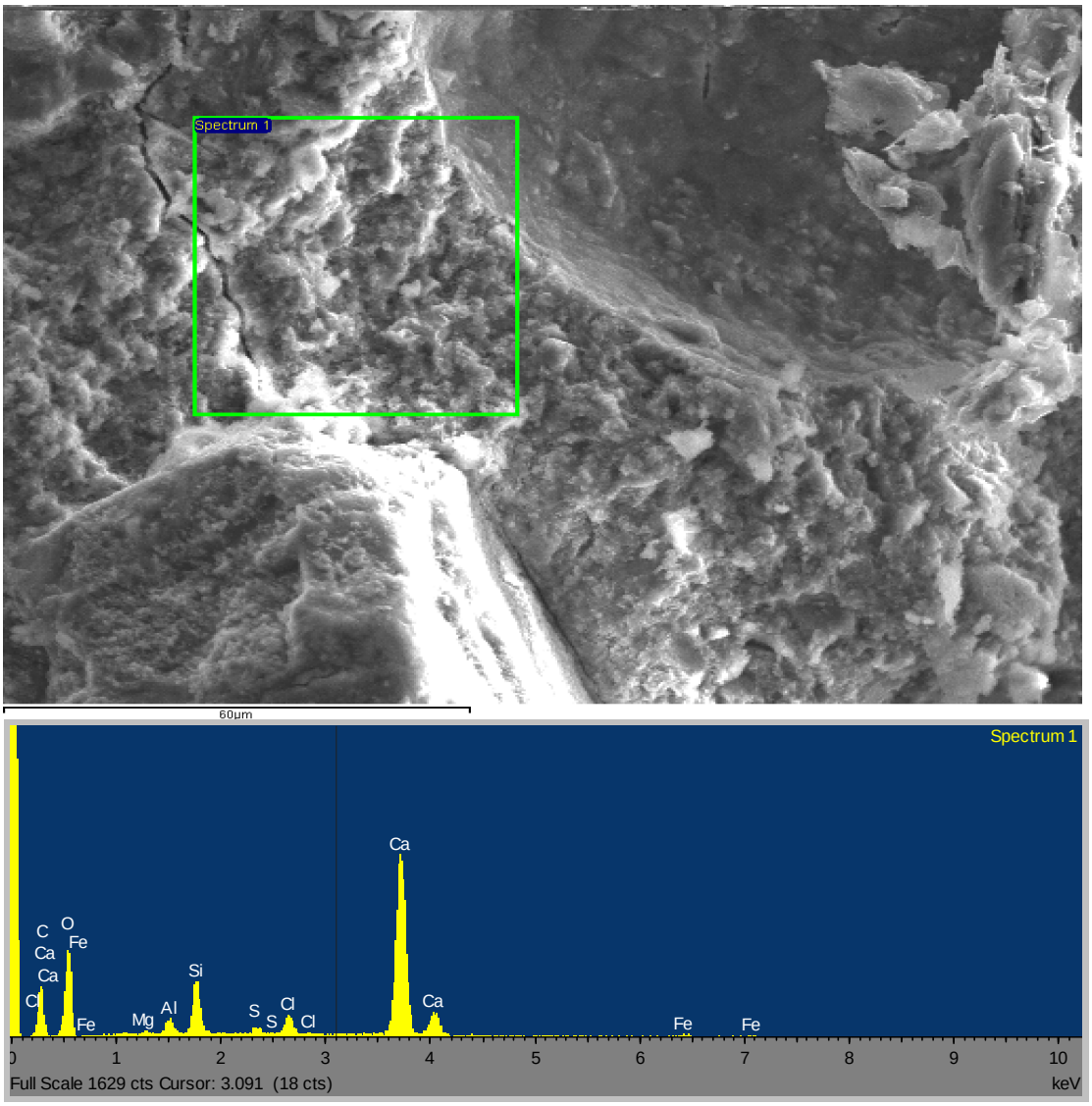
Element	O	Al	Si	K	Ca	Total
Weight, %	47.96	0.48	5.33	0.52	45.72	100.00

Figure 4.112. SEM micrograph and EDS spectra for mix AM2 (Specimen 2).



Element	O	Mg	Al	Si	S	Ca	Total
Weight, %	30.52	0.08	0.44	0.57	0.39	68.00	100.00

Figure 4.113. SEM micrograph and EDS spectra for specimen AM2 (Specimen 3).



Element	O	Mg	Al	Si	S	Cl	Ca	Fe	Total
Weight, %	47.13	0.40	1.29	5.49	0.88	2.87	40.22	1.73	100.00

Figure 4.114. SEM micrograph and EDS spectra for mix AM2 (Specimen 4).

Table 4.87. Results of SEM micrographs and EDS spectra of concrete specimens exposed to above ground conditions.

Mix #	**Cement Type**	**Pozzolan**	**Sulfur Content (%)**	**Aluminum Content (%)**	**Sulfate Attack**
AM1	I	None	0.92	1.18-1.42	Present
AM2	V	None	0.48	0.48-0.64	Present

4.4 Summary of Findings

The results of the present study are summarized in the following sub-sections.

4.4.1. Condition of the Specimens

The blended cement reinforced concrete beam specimens exposed to tidal zone, below ground and above ground conditions did not show any signs of deterioration after 10 years of exposure. Some of the beam specimens prepared with Type I cement exhibited minor cracking.

4.4.2. Corrosion of Reinforcing Steel

The corrosion potentials in the blended cement concrete specimens exposed to tidal, below ground and above ground conditions were more than -350 mV CSE indicating no active corrosion. However, the corrosion potentials in some of the beam specimens prepared with Type I were less than -350 mV CSE indicating active corrosion.

4.4.3. Chloride Concentration

The chloride concentration at the rebar level in all the concrete specimens placed in the tidal zone crossed the threshold chloride value of 0.15% by weight of cement. However, the chloride contents were generally less in the blended cement concrete than in the OPC cement concretes.

In the specimens exposed to the below ground condition, the chloride concentration at the rebar level was less than the threshold value in the cement concrete containing 8% silica fume or 30% fly ash. The chloride content in the OPC concrete specimens was generally more than the threshold value.

In the specimens exposed to above ground conditions, the chloride concentration at the rebar level was less than the threshold value in the cement concrete containing silica fume or fly ash. The chloride concentration in the OPC concrete specimens was generally more than the threshold value.

4.4.4. Sulfate Concentration in Concrete

The sulfate concentration at the rebar level did not correlate well with the type of cement. In the partially buried columns, the sulfate concentration in the below ground and above groundportions of pozzolanic concretes were comparable.

4.4.5. pH

The pH at the rebar level in all the concrete mixtures was more than 12.0, except in the 30% fly ash and 70% slag cement concrete mixtures, which exhibited marginally lower pH values due to the high cement replacement in these two pozzolanic materials.

4.4.6. Depth of Water Penetration

After ten years of exposure to tidal zone and below ground condition, all the pozzolanic concrete mixes performed well with the average permeability being less than 2.4 cm. The water permeability of specimens placed in the aboveground conditions continued to show higher values than the specimens exposed to tidal and below ground zones. The depth of water penetration in most of the specimens placed in the above ground zone was in the range of 10 to 15 cm.

4.4.7. Chloride Permeability

The chloride permeability of the pozzolanic cement concrete mixture was low to very low. On the other hand the chloride permeability of Type I and Type V mixtures was low to moderate.

4.4.8. Electrical Resistivity

After ten years of exposure in three main zones, the electrical resistivity of the pozzolanic concrete mixes was higher than the OPC concrete mixes and showed low risk of corrosion.

4.5. Comparison with other studies

Some of the results reported from the Treat Island Research Station indicated the following:

(i) The sulfate susceptibility of blended cements is becoming better understood and the use of certain blended cements promises to provide a useful alternative to moderately or highly sulfate-resisting Portland cements.

(ii) After about nine years of exposure, both normal-weight and lightweight air-entrained concretes showed no degradation of the mass of the concrete. However, some of the specimens showed significant surface deterioration. The amount of deterioration generally increased with increasing water-to-cementitious materials ratio, and increasing replacement of cement with slag and fly ash. It appears that surface deterioration can be avoided if the cement content is kept to at least a certain minimum level.

(iii) After nine years of exposure to the very severe conditions, the high-volume fly ash concrete prisms with a water-to-cementitious materials ratio of 0.31 were in excellent condition, but the concrete prisms with a water-to-cementitious materials ratio of 0.35exhibited some surface scaling.

The report on concrete performance reported from the St. Augustine Research Station indicated that the use of cement with C_3A in excess of 12% resulted in a concrete which low durability in warm seawater. The use of Type II cement with C_3A content of less than 8% was recommended for such exposure.

In 1936 researchers at the Technical University of Norway in Trondheim initiated a long termdurability study on the durability of concrete in an marine environment (Gjorv, 1971).Concrete specimens prepared with 313 kg/m^3 of total cementitious materials content and a water/cementitious materials ratio of 0.60 was were prepared, cured for 48 hours and thenimmersed in Trondheim's harbour. Seven different cements with C_3A contents between 3and 13% were tested with and without trass (volcanic tuft - a natural pozzolan) and slag. Cement was substituted with 60% trass, and 20 or 40% slag. The concrete prisms wereexposed to seawater that was never less than 1ºC for 30 years. It was reported that thecompressive strength of all the mixtures prepared with Portland cements having C_3Acontents of 6, 9 and 10% were unaffected by seawater, but those with 11 and 13% C_3Aexhibited a sharp decreasein strength after 10 years of exposure. In contrast, all mixtures containingPortland cement (except for the mixture with 11% C_3A), exhibited a progressive decrease inflexural strength starting from the 15th year of exposure, regardless of the C_3A content. Thisappears to indicate an inconsistency between the compressive and flexural specimens,because flexural strength is generally affected more by most forms of deterioration thancompressive strength. All four slag modified cements exhibited an increase in the compressivestrength for the first 15 years. However, after 30 years of exposure two of the slag mixtures exhibiteda decrease in the compressive and flexural strength. It is interesting to note that the latter slagcements had alumina (Al_2O_3) contents that were 42% less than those that did not losestrength.

In summary, the results reported by Gjorv (1971) demonstrate the concretes with w/cbetween 0.50 and 0.65 have poor long-term resistance to seawater attack, but that cementswith C_3A contents between 3 and 10% behaved similarly. Research by other workers(Malhotra and

Bremner, 1996) clearly show the benefits of maintaining w/c below 0.45 or0.40 and the use of supplementary cementing materials.

Based on the obtained results to date of the various corrosion and concrete properties, the pozzolanic concrete mixes performed better than the OPC concrete mixes. The studies conducted at other research stations indicate beneficial effects of low water cement ratio, high cement content and use of pozzolanic materials in concrete. The results of the present study agree with these results. The concrete specimens made with lower water cement ratio and those containing pozzolanic materials performed better.

CHAPTER 5

CONCLUSIONSAND RECOMMENDATIONS

5.1 Conclusions

1. After ten years of exposure, no noticeable deterioration was noted in the beam specimens exposed in the tidal zone for ten years, except for mixes TM9, TM10, TM12, TM16, TM19and TM20. Deposition of algae was noticed in almost all the specimens due to which the color of concrete changed to greenish black to black in some cases. Minor to major deposits of shells were noticed on the specimens with high density of shells found on the side facing the sea.

   There was no major noticeable deterioration in the columns exposed to the partially buried zone. Fine shrinkage cracks were noticed in the finished mortar on the mid-section of the column.

   No noticeable deterioration in cylindrical and cubical specimens buried under ground for ten years. Deposits of sand were seen on most of the specimens. While there was no changes of color in most of the specimen greenish black deposits of oil was noted on few. There was no noticeable deterioration in the cylinders and cubes exposed in above ground zone. The color of concrete specimens did not change. A thin film of dust accumulated on all the specimens.

2. The corrosion performance of the specimens in the main exposure zones can be summarized as follow:
   In the tidal zone, after more than 3650 days (ten years) all exposed beams showed more corrosion activity compared to the other zones due to the harsh exposure conditions. In the tidal zone, all the beams, except TM7 (8% SF), the average corrosion potentials remained numerically below -350 mV CSE. The corrosion potentials in all the other beams including the mixes with pozzolanic admixtures reinforcement showed corrosion potential values within the range of uncertain corrosion state.

   In the partially buried zone, the corrosion potential values in all the columns, remained numerically below -350 mV CSE in both the upper and lower portions, indicating the columns are in an inactive corrosion. In all the columns, the potentials measured on the

AG portion exhibited less negative behavior compared to the potentials measured on the IF and BG portions.

The corrosion potentials in the AG portion of all the columns were in inactive corrosion.

In the columns with low w/(c+SF) ratio, silica fume (SF) cements, Type V cement, FA, Superpozz, GGBFS, and FBEC reinforcement, the corrosion potentials both in the IF&BG and AG portions indicated state of *no active corrosion*.

3. The chloride concentration at the rebar level in all the concrete mixtures in the tidal zone crossed the threshold chloride value (0.025% by weight of concrete established by ACI 318), indicating the harsh exposure conditions with the reported values ranged between 0.04% and 0.138% by weight of concrete. The results indicate that the above ground exposure is less aggressive compared with the below ground exposure.

4. The sulfate concentration was between 0.1% and 0.2% with the lowest values noted in the concretes specimens prepared with high cement content, low w/c ratio + SF, 20% FA, and 10% Superpozz. However, there was no correlation between mixture composition and the sulfate concentration.

   In the partially buried columns, the sulfate concentration at the rebar level (72-77 mm), of the pozzolanic mixes in the below ground portion ranged between 0.086% and 0.121% and for the above ground portion it ranged between 0.086% and 0.110% which are very comparable to the reported concentrations for the other mixes.

   The pH at all depths, except the surface layer (i.e. 0 to 5 mm)was more than 12.0, which confirms the high alkalinity of bulk concrete for all types of mixtures. The pH at the rebar level in all the mixes was more than 12.0, except in mixes TM17 and TM20 (30% FA and 70% GGBFS, respectively) which exhibited marginally lower pH values due to the high cement replacement by these two pozzolanic materials. These data indicated that the high alkalinity of the concrete mixture, which is very important from corrosion perspective, is maintained in all the specimens.

5. The depth of water penetration in mixes M1 (Type I cement) and M2 (Type V cement) was almost similar. All the pozzolanic concrete mixes have performed well with the average permeability being less than 2.4 cm. The water permeability of specimens exposed to the aboveground conditions was more than that of specimens exposed to tidal and below ground zones. The depth of water penetration in most of the specimens exposed to the above ground zone was in the range of 10 to 15 cm.

6. The overall rating of concrete quality with regard to chloride permeability for most of concrete mixes ranged from very low to moderate. In the tidal zone, all the pozzolanic concrete mixes showed very low to low chloride permeability with the exception of mix M20 (with 70% GGBFS). The best performance was noted in concrete mix M8 (20% FA), M15 (10% Superpozz) and M17 (30% FA) with values less than 500 Coulombs. The chloride permeability of most of the concrete mixes exposed to the below ground zone was in very low to low range. The chloride permeability of all the pozzolanic concrete mixes was in the very low to low range.

7. The electrical resistivity of concrete specimens placed in the tidal zone ranged from 31.18 to 113.10 kOhm.cm with the corresponding moisture content values of 2.45 and 2.76%. At 3% moisture content, the electrical resistivity values were in the range of18.99 kOhm.cm to 199.24 kOhm.cm.

   The electrical resistivity decreased for most of the mixes placed in the below ground zone, with values ranging from 24.61 to 326.09 kOhm-cm with the corresponding moisture content values of 2.95 and 4.11%, respectively. The initial electrical resistivity of pozzolanic concrete mixtures, such as Mixes M7 (8% silica fume), M8 (20% FA), M15 (10% Superpozz) and M20 (70% GGBFS) was high being more than 100 kOhm-cm indicating negligible risk of corrosion. Similarly, at 3% moisture content the electrical resistivity values of these concrete mixtures was also more than100 kOhm.cm.

   The electrical resistivity of all the concrete specimens placed in the atmospheric exposure conditions was in the range of 50 to 100 kOhm.cm with low risk of corrosion with the exception of mixes M7 (8% SF) and M20 (70% GGBFS). Among all the exposure conditions, the electrical resistivity values of the atmospheric exposure specimens are the highest for all the concrete mixes at the initial and for some mixes at 3% moisture content.

7. The water absorption of the concrete specimens exposed in the tidal zone was the least followed by the specimens exposed to belowground and above ground conditions. The water absorption values of all the mixes exposed in the tidal zone ranged from 3.53 to 4.60%.

   With the exception of mix M20, the water absorption values of all the mixes exposed to the above ground conditions fall within a narrow range of 3.9 to 4.39%. The water absorption of mix M1 (Type I cement) was similar to that of mix M2 (Type V cement), with the water absorption values of 4.01 and 4.18%, respectively.

8. The compressive strength of specimens exposed to below ground conditions was more than that of specimens exposed to above ground and tidal zones. This is attributed to the ongoing hydration of cements by the ground water. Mixes M3 (high cement content) and M4 (8% SF and 0.3 w/c ratio) were the best in the below ground and M17 (with FA) was the best in the above ground zone, while mix M1 with Type I cement it were the best in the tidal zone.

9. Carbonation in the tidal zone was reported only in mixes M13 (Standard mix), and M17 (30% fly ash) with depths ranging from 1.0 to 1.5 mm which is very low. In the below ground exposure, negligible carbonation was reported only in mix M1 (Type I cement). In the upper portions of the columns exposed to atmosphere, carbonation after was reported in mixes M1 (Type I cement), M3 (High cement content), M8 (20% FA), with depths ranging from 4 mm to 12 mm. With the exception of mix M8, carbonation was not noted in all the pozzolanic mixes. The depth of carbonation in the above ground portions of the columns was more than that noted in the tidal and below ground zones due to the continuous and direct exposure of these specimens to the atmospheric carbon dioxide.

10. The SEM micrographs and EDS spectra did not indicate signs of sulfate attack in the Type I cement concrete containing silica fume or blast furnace slag and exposed to the tidal zone. However, formation of ettringite due to the sulfate attack was noted in Type I cement concrete made with fly ash.

    Sulfate attack was not evident in Type V, fly ash and silica cement concretes exposed to the soil environment. However, the formation of ettringite due to the sulfate attack was noted in the blast furnace slag cement concrete exposed to the below ground conditions.

5.2 Recommendations

Based on the obtained results to date of the various corrosion and concrete properties, the pozzolanic concrete mixes performed better than the OPC concrete mixes. The studies conducted at other Research Stations indicate the beneficial effects of low water cement ratio, higher cement content and use of pozzolanic materials in concrete. The results of the present study agree with these results. Therefore, it is recommended to use low water to cementitious materials ratio (Less than 0.4), high cement content (Minimum 375 kg/m^3) and blended cement concretes for all the exposure conditions in the Royal Commission construction sites.

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